Configuration Risk Management Analyses For Crystal River Unit 3

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Contents

Acronyms

ASP	Accident Sequence Precursor
ASEP	Accident Sequence Evaluation Program
BNL	Brookhaven National Laboratory
CCF	common cause failure
DEEM	Daily Events Evaluation Manual
INEL	Idaho National Engineering Laboratory
IPE	Individual Plant Examination
LOCA	loss of coolant accident
MLD	master logic diagram
PRA	probabilistic risk assessment
SRM	simplified risk model

Configuration Risk Management Analyses For Crystal River Unit 3

The Crystal River Unit 3 plant risk model is made up of a master logic diagram (MLD) and associated basic event data. This MLD is a single fault tree representing the dominant accident sequences [as defined by the probabilistic risk assessment (PRA) event trees]. Thus, the top gate of this fault tree represents core damage. This MLD is used by the plant personnel for the plant "risk monitor." Also, Brookhaven National Laboratory (BNL) and the Idaho National Engineering Laboratory (INEL) used this same MLD to investigate various plant configurations for a six month span of 1995 operational data. This report discusses the model used for the analysis, sensitivity calculations for important configurations, and general issues related to the analyses that were performed. Specifically, the topics of presentation are:

- The Crystal River risk model
- The SAPHIRE Representation of the Crystal River Risk Model
- Core Damage Results for Nominal Configuration
- Effects of Recovery Actions on Nominal Core Damage Results
- Sensitivity to Truncation of Nominal Core Damage Results
- Core Damage Results for Important Configurations of Interest
- Effects of Recovery Actions on Important Configurations
- Sensitivity to Truncation of Important Configurations
- Treatment of Common-Cause Failure Events
- Comparison of MLD to Simplified Plant Risk Model

1.0 Crystal River Risk Model

The Crystal River MLD is a single large fault tree containing approximately 4,500 gates and 2,500 basic events. The MLD represents the dominant accident sequences as defined in the PRA event trees. The individual plant examination (IPE) lists 17 accident sequences that were analyzed for the IPE submittal [seven transient, two small-break loss-of-coolant-accident (LOCA), two medium-break LOCA, two large-break LOCA, and four steam generator tube rupture sequences].[1]

A concern with the MLD is that it may only represent the dominant (from the perspective of the nominal or base-case conditions) accident sequences. If the nondominant accident sequences are not included in the MLD, application of the MLD may yield incorrect results when evaluating configurations deviating from nominal conditions. While some PRA models may have several dozen dominant accident sequences, the total number of possible accident sequences from these models may range in the hundreds to thousands. Ignoring the nondominant sequences has been problematic when using PRA models for risk-based applications. But, since the actual number and characteristics of the accident sequences contained in the Crystal River MLD were not indicated and can not easily be determined from the MLD, the overall impact of discarding nondominant accident sequences is unknown at this time.

A second concern with the MLD concept is that problems may arise due to the treatment of success paths in the accident sequence. Core damage accident sequences consist of an initiating event followed by both failed and nonfailed systems. There are various methods of handling the nonfailed part of the accident sequence. For example, some PRA analysis codes can perform what is called a "delete term" operation where impossible events are removed from the resulting sequence cut sets. Impossible events are those events that are both failed and nonfailed in the same sequence. Alternatively, some PRA analysis codes can solve the complemented logic (for the nonfailed systems) along with the failure logic (for the failed systems), resulting in a noncoherent system. Solving cut sets for noncoherent systems is somewhat more difficult than evaluating failure logic exclusively and requires longer analysis time. Use of the MLD concept makes the assumption that the probability of having a nonfailed system is 1.0 (which is a conservative assumption, but for most systems modeled in PRA, the nonfailed probability is close to 1.0). Once core damage cut sets are generated with the MLD, the cut sets could be postprocessed in order to remove events thought to be impossible.

The Crystal River MLD does use a postprocessing file to manipulate the cut sets, but this step is performed to remove mutually exclusive events (e.g., double testing/maintenance) or to append recovery actions to the cut sets. In order to remove impossible events, the MLD would have to somehow "tag" the cut sets in order to let the postprocessor know what accident "sequence" yielded the cut sets. This tag would be required because the cut set X * Y * Z may contain impossible events for sequence A-1 but could be completely correct for sequence A-2. It does not appear that impossible events are being removed from the resulting cut sets that are generated from the Crystal River MLD. Consequently, since extra cut sets are being generated from the MLD that, in reality, may be impossible, the core damage frequency will be higher than the frequency obtained from rigorous treatment of the nonfailed systems. The magnitude of the overestimate when using the MLD is unknown, but it is expected to be small. This issue of ignoring the "delete term" operation and the resulting impact on the core damage frequency is left for future work.

Since the MLD is a single, large fault tree, it consists of logic gates and inputs (i.e., basic events) to these gates. The basic events in the model have one of two types of reliability models assigned to them. The first model used is a simple demand type of failure. Thus, a mean failure probability is assigned to the basic event. The second model used a "fails to run" model where the parameter of interest is a failure rate. The failure rate is used to calculate a probability of failure for the mission time (which is assumed to be constant) using the equation:[2]

$$P(failure) = 1 - e^{-(\lambda \cdot Mission\ Time)}$$

For each of the parameters (i.e., demand failure probability for the first model and the failure rate for the second model), an uncertainty distribution was assigned. In the Crystal River model, every parameter was assigned a lognormal distribution. For these lognormal distributions, the error factor was specified.

2.0 SAPHIRE Representation of the Crystal River Risk Model

In order to develop the SAPHIRE Crystal River MLD, several pieces of information had to be collected and converted from one format to another. The fault tree logic was converted from the CAFTA format to the MAR-D format (the format supported by the SAPHIRE software[3]) using the utilities supplied by SAIC as part of their R&R Workstation package.[4] This MAR-D logic file was then manually edited to convert gates that were not correctly translated by the R&R Workstation data filter. The MAR-D fault tree file was then broken into several separate subtrees by using the SAPHIRE pager utility. These fault tree files were then loaded into the IRRAS software using the MAR-D input routines.

The basic event data were converted from the CAFTA reliability database format into a "fixed format" text file. This text file consisted of data such as basic event name, basic event description, reliability model type, mean probability or failure rate, and uncertainty parameter. A BASIC program was written to parse the text file and output a MAR-D-compatible basic event information file (*.BEI) and basic event description file (*.BED). These files were then loaded into the IRRAS software using the MAR-D input routines.

The CAFTA post-processing file (a list of rules to either remove a cut set from the results or append a recovery action to a cut set) was converted to the MAR-D system recovery rules format (*.FAS). A second BASIC program was written to convert the rule structure from the CAFTA format to the MAR-D format. Both the post-processing files for the module rules and basic event rules were converted, but only the module rules file was used in IRRAS (the Crystal River plant risk module uses only the module rules file).

Lastly, data correlation for the basic events was specified manually for those events that were not already assigned correlation classes by the basic event data conversion BASIC program. The BASIC program that converted basic event data assigned events to the same correlation class if the event used the same failure rate data from the *.TC (TC stands for "type code," but really represents a failure rate database) file. Out of the approximately 2,500 basic events, almost two-thirds of the events were automatically assigned to the proper correlation class. This automatic assignment left about one-third of the basic events without correlation classes. If these events were left as-is, this would imply that no data correlation exists among the events, which is incorrect for many of the events (e.g., many event probabilities were derived from the same data source). These uncorrelated events were gathered and sorted in order to manually correlate the events (e.g., many of the human error probabilities have a data dependency). Thus, the SAPHIRE database contains basic events that are correlated based upon data dependencies due to one of two cases: (1) multiple use of the failure rates in the "type code" database or (2) data correlation between demand failure probabilities. The Crystal River MLD model exercised by BNL and SAIC does not have the additional data correlations for the second case, and consequently, the uncertainty analysis results may be different when comparing the BNL and INEL analyses.

3.0 Core Damage Results for Nominal Configuration

The SAPHIRE Crystal River plant risk MLD was used with IRRAS (version 6.x) to obtain the overall core damage frequency (both before and after applying recovery actions), uncertainty on the core damage frequency, dominant cut sets, and importance measures. Since the plant risk monitor (which uses the MLD) uses a frequency truncation level of 1E-7/yr and the plant PRA personnel routinely use 1E-8/yr as a truncation level, the nominal results for the SAPHIRE MLD were generated using a cut off level of 1E-8/yr. The results of the cut set generation give a minimal cut set upper bound (min-cut) of 1.1E-4/yr (this is the "before recovery" value, the "after recovery" results will be presented in the next section). The top 26 dominant cut sets are shown in Table 1. These cut sets were generated using the nominal probabilities for every basic event except testing and maintenance events. All testing and maintenance events were assigned a zero probability since the nominal case will be used as a reference point for the core damage frequency in various configurations. These various configurations will have actual testing and maintenance outages "mapped" directly into the model. Consequently, the model testing and maintenance "randomness" has been taken out of the PRA. Instead, the analysis requires modifications to the model based upon actual testing or maintenance outages during the configuration of interest.

Upon evaluation of the top 26 dominant nominal cut sets, two items become obvious. First, several "flags" (e.g., TBUFLAG, XFLAG) appear in the cut sets instead of actual recovery actions. These flags are used in the application of recovery actions. Second, some cut sets contain more than one initiating event. For example, cut sets #12, #13, and #14 both contain two transient initiating events in each cut set. These cut sets will be removed after the application of "recovery" rules. In general though, the cut sets that are generated before recovery rules are applied could be very different from the end results.

4.0 Effects of Recovery Rules on Nominal Core Damage Results

Exploring the effects of recovery rules on the nominal core damage cut sets is complicated due to the application of the rules for two separate purposes. First, the recovery rules are used to remove impossible cut sets or cut sets containing mutually exclusive basic events. An example of this application would be the removal of cut sets containing more than one initiating event. Since the MLD concept requires that initiating events be included in the fault tree logic, it is possible to have cut sets with more than one initiating event. Typically, PRA methods ignore the potential of having simultaneous initiating events unless one initiator leads to another (e.g., a transient leading to a small-LOCA).

The second application of the recovery rules is to append appropriate recovery action events onto the cut sets. If a system or component fails but can be recovered by operator intervention, the PRA results should account for this operator action. Consequently, many cut sets will have an event (or events) appended to the cut sets representing the probability that the operator fails to recover or restore the failed component or system. These operator action basic events are assigned nonrecovery probabilities.

Table 1. Top 26 core damage cut sets from the Crystal River MLD (nominal configuration, before recovery actions are applied).

#	Frequency/Event	Basic event description
1	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
2	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
3	8.132E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
4	8.132E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
5	4.445E-006	
	ADGCCFTS	EDG CCF TO START NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
6	4.445E-006	
	ADGCCFTS	EDG CCF TO START NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
7	3.223E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
8	3.223E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BA	EDG-3B FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
9	3.223E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
10	3.223E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
11	2.000E-006	
	XFLAG	HPR RECOVERY FLAG
	XHPR12H	OPERATOR FAILS TO GO TO HPR (12H) HRA
	S	SMALL BREAK LOCA OCONEE IPE
12	1.713E-006	
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	T8	LOSS OF 4160V ES BUS 3A IE
	TBUFLAG	TBU RECOVERY FLAG
13	1.713E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
14	1.713E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
	TBUFLAG	TBU RECOVERY FLAG

Table 1. Cont.

#	Frequency/Event	Basic event description
15	1.713E-006	
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	T8	LOSS OF 4160V ES BUS 3A IE
16	1.278E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
17	1.278E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BA	EDG-3B FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
18	1.088E-006	
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	T10	LOSS OF NSCCC IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
19	1.088E-006	
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	T10	LOSS OF NSCCC IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
20	6.788E-007	
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	T8	LOSS OF 4160V ES BUS 3A IE
	TBUFLAG	TBU RECOVERY FLAG
21	6.788E-007	
	ADGES3BA	EDG-3B FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	T8	LOSS OF 4160V ES BUS 3A IE
22	6.788E-007	
	ADGES3AA	EDG-3A FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
	TBUFLAG	TBU RECOVERY FLAG
23	6.788E-007	
	ADGES3AA	EDG-3A FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
24	6.484E-007	
	JPMAH1AA	COMPRESSOR AHP-1A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
25	6.484E-007	
	JPMAH1CA	COMPRESSOR AHP-1C FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
26	6.484E-007	
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	SPMRW2AA	RWP-2A FAILS TO START

When we apply the recovery rules to the generated cut sets, both applications described above are performed. It is not interesting to estimate the overall effect on cut sets due to the first application (removal of impossible cut sets or cut sets with mutually exclusive events). Those cut sets that will be removed by the rules should not appear in the final core damage cut sets. Alternatively, the impact of operator actions on the cut sets could be of interest. While we need to include both applications of the recovery rules to our final resulting cut sets, to investigate the impact of operator actions we will need to first apply only the cut set removal application and then perform the sensitivity analysis for the second (i.e., appending operator recovery actions) application.

Performing the operator action sensitivity calculation required multiple steps in the cut set generation process. First, the nominal cut sets were generated (at a 1E-8/yr truncation level) and were shown in Table 1. Second, the cut sets for just the rules that remove impossible cut sets or cut sets with mutually exclusive events were applied. The top 27 cut sets for this case are shown in Table 2. The overall min-cut for the core damage frequency is 8.9E-5/yr. Third, the recovery rules were applied that appended recovery actions where appropriate. The top 24 cut sets for this case are shown in Table 3. The overall min-cut for the core damage frequency is 9.5E-6/yr. The results of the operator action sensitivity analysis for the nominal configuration are summarized below.

Case	Core damage frequency (per year) min-cut	Total number of cut sets greater than 1E-8/yr frequency
Before any recovery rules are applied	1.1E-4/yr	420
After removing impossible cut sets and mutually exclusive events	8.9E-5/yr	313
After removing impossible cut sets and mutually exclusive event and appending operator recovery actions	9.5E-6/yr	123

As can be seen from the above results, the application of the recovery rules that only remove impossible cut sets or mutually exclusive events eliminates 107 cut sets and drops the core damage frequency about 20%. The application of the recovery rules that append the operator recovery actions removes an additional 190 cut sets while further dropping the core damage frequency by about 90%. Consequently, the recovery action modeling reduces the core damage frequency by an almost order of magnitude for the nominal configuration. This order-of-magnitude change may not be unreasonable since the change represents the probability that operators do not restore inoperable components.

Table 2. Top 27 cut sets from the Crystal River MLD (nominal configuration, after removing impossible cut sets and mutually exclusive events but before including recovery actions).

#	Frequency/Event	Basic event description
1	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
2	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
3	8.132E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
4	8.132E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
5	4.445E-006	
	ADGCCFTS	EDG CCF TO START NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
6	4.445E-006	
	ADGCCFTS	EDG CCF TO START NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
7	3.223E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
8	3.223E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
9	3.223E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
10	3.223E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BA	EDG-3B FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
11	2.000E-006	
	XFLAG	HPR RECOVERY FLAG
	XHPR12H	OPERATOR FAILS TO GO TO HPR (12H) HRA
	S	SMALL BREAK LOCA OCONEE IPE
12	1.278E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
13	1.278E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BA	EDG-3B FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
14	6.484E-007	
	JPMAH1AA	COMPRESSOR AHP-1A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.

Table 2. Cont.

#	Frequency/Event	Basic event description
15	6.484E-007	
	JPMAH1CA	COMPRESSOR AHP-1C FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
16	6.484E-007	
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	SPMRW2AA	RWP-2A FAILS TO START
	TBUFLAG	TBU RECOVERY FLAG
17	6.484E-007	
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	SPMSWPAA	SWP-1A FAILS TO START
	TBUFLAG	TBU RECOVERY FLAG
18	6.484E-007	
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	SPMRW2AA	RWP-2A FAILS TO START
19	6.484E-007	
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	SPMSWPAA	SWP-1A FAILS TO START
20	5.100E-007	
	LMV0043X	DHV-43 ALIGNED OPEN LGENMEC1
	LUFLAG	HPI RECOVERY FLAG
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407
21	5.100E-007	
	LMV0042X	DHV-42 ALIGNED OPEN LGENMEC1
	LUFLAG	HPI RECOVERY FLAG
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407
22	5.000E-007	
	XFLAG	HPR RECOVERY FLAG
	M	MEDIUM BREAK LOCA NUREG/CR-4407
	XHPR12H	OPERATOR FAILS TO GO TO HPR (12H) HRA
23	4.879E-007	
	HO043H	CREW FAILS TO START RWP-2A IN 3.5 HRS HRA
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
24	4.444E-007	
	LMVSVCCF	DHV-42|43 CCF TO OPEN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	S	SMALL BREAK LOCA OCONEE IPE
25	4.444E-007	
	LMVRVCCF	DHV-11|12 CCF TO OPEN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	S	SMALL BREAK LOCA OCONEE IPE
26	4.007E-007	
	LMV0043R	DHV-43 TRANSFERS OPEN
	LUFLAG	HPI RECOVERY FLAG
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407
27	4.007E-007	
	LMV0042R	DHV-42 TRANSFERS OPEN
	LUFLAG	HPI RECOVERY FLAG
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407

Table 3. Top 24 cut sets from the Crystal River MLD (nominal configuration, after removing impossible cut sets and mutually exclusive events and appending recovery actions).

#	Frequency/Event	Basic event description
1	2.000E-006	
	XFLAG	HPR RECOVERY FLAG
	XHPR12H	OPERATOR FAILS TO GO TO HPR (12H) HRA
	S	SMALL BREAK LOCA OCONEE IPE
2	7.009E-007	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
	AC024H	OFFSITE POWER NOT RESTORED IN 4HR 50MIN NUREG-1032
3	5.042E-007	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
	AC024H	OFFSITE POWER NOT RESTORED IN 4HR 50MIN NUREG-1032
4	5.000E-007	
	XFLAG	HPR RECOVERY FLAG
	M	MEDIUM BREAK LOCA NUREG/CR-4407
	XHPR12H	OPERATOR FAILS TO GO TO HPR (12H) HRA
5	4.444E-007	
	LMVSVCCF	DHV-42|43 CCF TO OPEN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	S	SMALL BREAK LOCA OCONEE IPE
6	4.444E-007	
	LMVRVCCF	DHV-11|12 CCF TO OPEN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	S	SMALL BREAK LOCA OCONEE IPE
7	2.756E-007	
	ADGCCFTS	EDG CCF TO START NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
	AC024H	OFFSITE POWER NOT RESTORED IN 4HR 50MIN NUREG-1032
8	2.505E-007	
	XFLAG	HPR RECOVERY FLAG
	QAVMS26C	MSV-26 (ADV) FAILS TO CLOSE ON DEMAND
	XHPR12H	OPERATOR FAILS TO GO TO HPR (12H) HRA
	T5	STEAM/FEEDLINE BREAK IE
9	1.998E-007	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
	AC024H	OFFSITE POWER NOT RESTORED IN 4HR 50MIN NUREG-1032
10	1.998E-007	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
	AC024H	OFFSITE POWER NOT RESTORED IN 4HR 50MIN NUREG-1032
11	1.642E-007	
	JCHHE02A	CHILLER| UNIT| CHHE-2 FAILS TO START
	PAFWH	CREW FAILS TO START AFW IN 15 MIN. HRA
	T10	LOSS OF NSCCC IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
12	1.611E-007	
	JCHHE02A	CHILLER| UNIT| CHHE-2 FAILS TO START
	HPMRCPTY	CREW FAILS TO TRIP RCPs (NO INJ OR CLG) HRA
	T10	LOSS OF NSCCC IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG

Table 3. Cont.

<table>
<tr><th>#</th><th>Frequency/Event</th><th>Basic event description</th></tr>
<tr><td>13</td><td>1.611E-007</td><td></td></tr>
<tr><td></td><td>JCHHE02A</td><td>CHILLER| UNIT| CHHE-2 FAILS TO START</td></tr>
<tr><td></td><td>HPMRCPTY</td><td>CREW FAILS TO TRIP RCPs (NO INJ OR CLG) HRA</td></tr>
<tr><td></td><td>XFLAG</td><td>HPR RECOVERY FLAG</td></tr>
<tr><td></td><td>T10</td><td>LOSS OF NSCCC IE</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td>14</td><td>1.413E-007</td><td></td></tr>
<tr><td></td><td>LUFLAG</td><td>HPI RECOVERY FLAG</td></tr>
<tr><td></td><td>HPM001CA</td><td>MUP-1C FAILS TO START</td></tr>
<tr><td></td><td>HMV0073N</td><td>MUV-73 FAILS TO OPEN ON DEMAND</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td></td><td>R</td><td>STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407</td></tr>
<tr><td>15</td><td>1.119E-007</td><td></td></tr>
<tr><td></td><td>LPMCCFTS</td><td>DHP-1A|1B CCF TO START NUREG-1150</td></tr>
<tr><td></td><td>XFLAG</td><td>HPR RECOVERY FLAG</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td></td><td>S</td><td>SMALL BREAK LOCA OCONEE IPE</td></tr>
<tr><td>16</td><td>1.111E-007</td><td></td></tr>
<tr><td></td><td>LMVSVCCF</td><td>DHV-42|43 CCF TO OPEN NUREG-1150</td></tr>
<tr><td></td><td>XFLAG</td><td>HPR RECOVERY FLAG</td></tr>
<tr><td></td><td>M</td><td>MEDIUM BREAK LOCA NUREG/CR-4407</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td>17</td><td>1.111E-007</td><td></td></tr>
<tr><td></td><td>LMVRVCCF</td><td>DHV-11|12 CCF TO OPEN NUREG-1150</td></tr>
<tr><td></td><td>XFLAG</td><td>HPR RECOVERY FLAG</td></tr>
<tr><td></td><td>M</td><td>MEDIUM BREAK LOCA NUREG/CR-4407</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td>18</td><td>1.051E-007</td><td></td></tr>
<tr><td></td><td>LRV0069N</td><td>BWST VACUUM BREAKER FAILS TO OPEN</td></tr>
<tr><td></td><td>LRV0070N</td><td>BWST VACUUM BREAKER FAILS TO OPEN</td></tr>
<tr><td></td><td>LUFLAG</td><td>HPI RECOVERY FLAG</td></tr>
<tr><td></td><td>R</td><td>STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407</td></tr>
<tr><td>19</td><td>1.039E-007</td><td></td></tr>
<tr><td></td><td>JCHHE02A</td><td>CHILLER| UNIT| CHHE-2 FAILS TO START</td></tr>
<tr><td></td><td>T10</td><td>LOSS OF NSCCC IE</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td></td><td>TBUFLAG</td><td>TBU RECOVERY FLAG</td></tr>
<tr><td></td><td>PMSTTF</td><td>TURBINE FAILS TO TRIP GIVEN REACTOR TRIP SCREENING</td></tr>
<tr><td>20</td><td>1.006E-007</td><td></td></tr>
<tr><td></td><td>ADGCCFTR</td><td>EDG CCF TO RUN NUREG-1150</td></tr>
<tr><td></td><td>XFLAG</td><td>HPR RECOVERY FLAG</td></tr>
<tr><td></td><td>T3</td><td>LOSS OF OFFSITE POWER IE</td></tr>
<tr><td></td><td>AC0512H</td><td>FAILURE TO RESTORE OFFSITE POWER IN 12H NUREG-1032</td></tr>
<tr><td>21</td><td>9.350E-008</td><td></td></tr>
<tr><td></td><td>A</td><td>LARGE BREAK LOCA NUREG/CR-4407</td></tr>
<tr><td></td><td>XALPRH</td><td>OPERATOR FAILS TO GO TO LPR (30M) HRA</td></tr>
<tr><td>22</td><td>8.548E-008</td><td></td></tr>
<tr><td></td><td>LMVDV11N</td><td>DHV-11 FAILS TO OPEN</td></tr>
<tr><td></td><td>LMV0043N</td><td>DHV-43 FAILS TO OPEN</td></tr>
<tr><td></td><td>XFLAG</td><td>HPR RECOVERY FLAG</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td></td><td>S</td><td>SMALL BREAK LOCA OCONEE IPE</td></tr>
<tr><td>23</td><td>8.548E-008</td><td></td></tr>
<tr><td></td><td>LMV0042N</td><td>DHV-42 FAILS TO OPEN</td></tr>
<tr><td></td><td>LMV0043N</td><td>DHV-43 FAILS TO OPEN</td></tr>
<tr><td></td><td>XFLAG</td><td>HPR RECOVERY FLAG</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td></td><td>S</td><td>SMALL BREAK LOCA OCONEE IPE</td></tr>
<tr><td>24</td><td>8.548E-008</td><td></td></tr>
<tr><td></td><td>LMVDV12N</td><td>DHV-12 FAILS TO OPEN</td></tr>
<tr><td></td><td>LMV0042N</td><td>DHV-42 FAILS TO OPEN</td></tr>
<tr><td></td><td>XFLAG</td><td>HPR RECOVERY FLAG</td></tr>
<tr><td></td><td>HNOMAINT</td><td>NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.</td></tr>
<tr><td></td><td>S</td><td>SMALL BREAK LOCA OCONEE IPE</td></tr>
</table>

Reviewing Table 2, we can verify that the impossible cut sets and mutually exclusive events have indeed been removed from the resulting cut sets. For example, the cut sets that contained more that one initiating event have been removed from the list. Upon reviewing the cut sets in Table 3, it is evident that the recovery actions applicable to the cut sets have been appended by the recovery rules. For example, for the cut sets that have the initiating event representing the loss of offsite power, the recovery action modeling the nonrecovery of offsite power in four hours and 50 minutes has been appended to the cut set.

As part of the "after recovery" analyses, the parameter uncertainties for the basic events were propagated through the model using both Latin Hypercube and Monte Carlo sampling methods. As discussed previously, the basic events in the MLD that had data dependencies were assigned to the same correlation class. Consequently, these basic events will be treated by IRRAS as being completely correlated (i.e., a correlation coefficient of 1.0). Also, since any rigorous Monte Carlo-type of uncertainty analysis should demonstrate some level of convergence, the uncertainty analysis was performed for increasing numbers of sampling iterations. The overall results of the uncertainty analysis are shown in Figure 1.

As can been seen in Figure 1, the convergence of the uncertainty sampling begins around several hundred samples. Both the Monte Carlo and Latin Hypercube sampling show similar convergence for this configuration. The results of the uncertainty analysis indicate that the mean core damage frequency is 8E-6/yr while the 95th percentile is 3E-5/yr. These values compare to the min-cut core damage frequency of 9.5E-6/yr. Thus, the mean core damage frequency is slightly lower than the point estimate min-cut for the nominal configuration. Using Figure 1 as an indication of the uncertainty convergence, it is judged that uncertainty analyses with more than 3,000 to 4,000 samples should demonstrate convergence.

Figure 2 shows a plot of basic event ranking for the Birnbaum importance measure versus the Fussell-Vesely measure. The importance measures for the plot were generated by using the nominal configuration and a truncation level of 1E-10/yr. The scatter on the plot indicates that there is little correlation between the two importance measures. For example, basic event LTKBWSTJ, DHT-1 fails (i.e., borated water storage tank failure), has a high Birnbaum measure (ranked first) but a low Fussell-Vesely measure (ranked 158th). Basic event AC024H, offsite power not restored in four hours, 50 minutes, has a low Birnbaum measure (ranked 195th) but a high Fussell-Vesely (ranked 7th). This lack of correlation between Birnbaum and Fussell-Vesely measures is typical for PRA models.

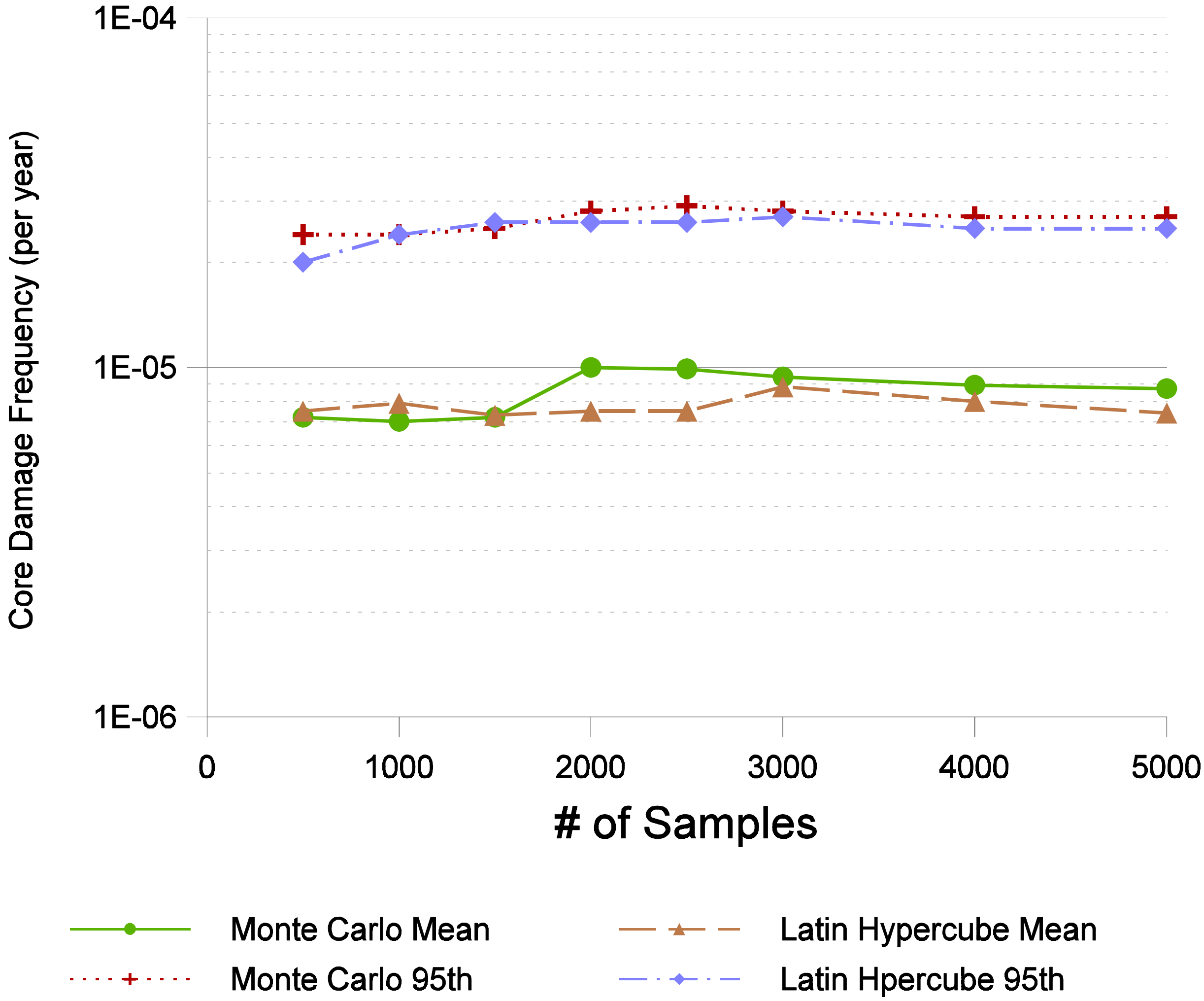

Figure 1. Monte Carlo and Latin Hypercube uncertainty propagation results for nominal case after applying recovery rules.

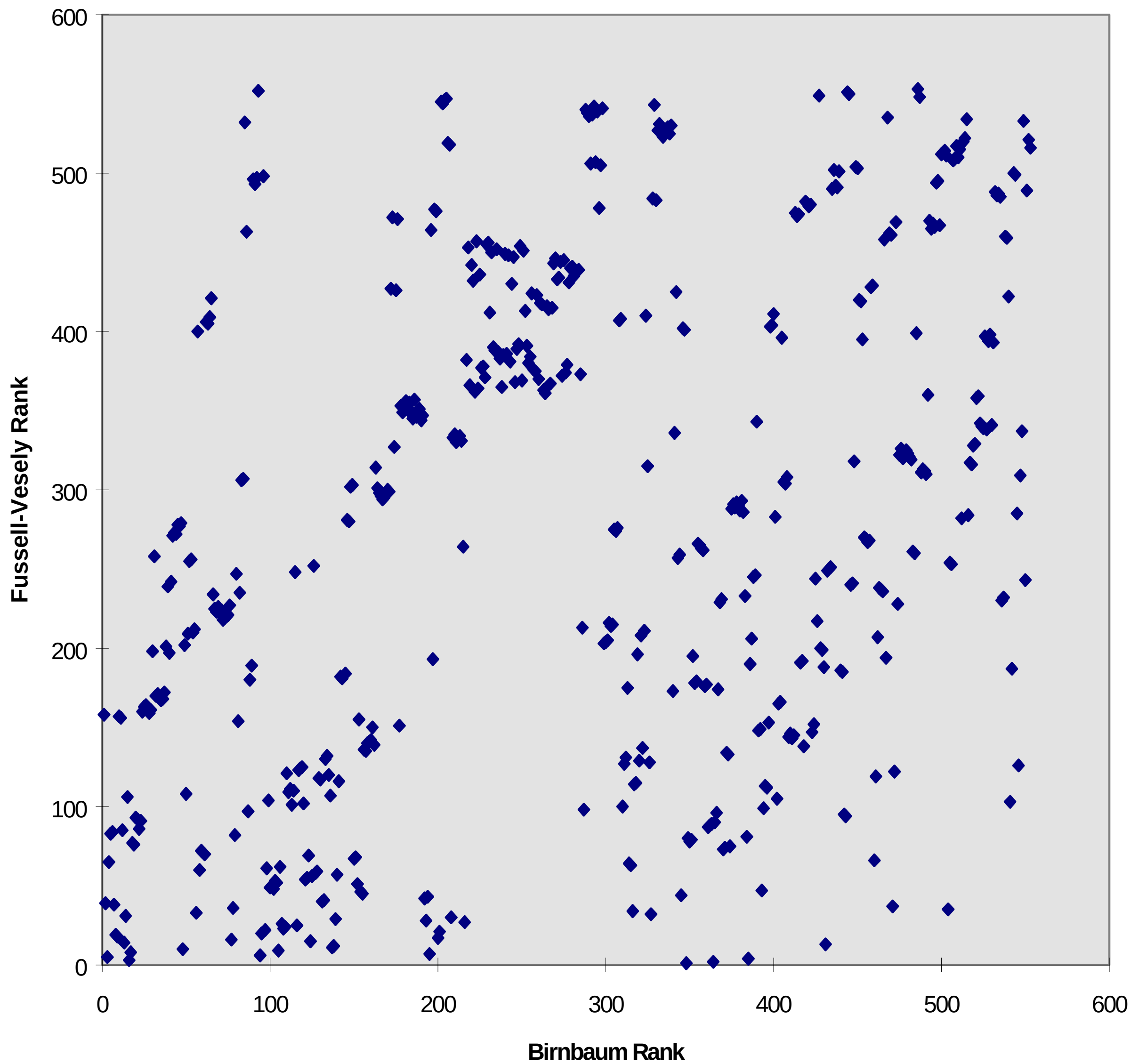

Figure 2. Basic event rankings for the list of Birnbaum importance measures versus the list of Fussell-Vesely importance measures.

An issue of importance to risk-based applications such as configuration management and event evaluations is the application and net impact of the recovery actions (which are normally developed only for dominant sequence cut sets) on nondominant sequences made dominant by a particular configuration. For example, because the Crystal River IPE indicates that steam generator tube ruptures (SGTR) account for only 5% of the overall core damage frequency, the question is raised concerning the correctness of the resulting core damage frequency for a SGTR event assessment if the MLD is used for the event assessment. To answer this question, one would have to review both the recovery rules that are used to append recovery actions to the core damage cut sets and the resulting cut sets.

To further illustrate the complexity of recovery modeling, an excerpt of the recovery rules used for the Crystal River MLD is shown below.

```
|**RECOVERY** AC024H 6.20E-02
if T3 * ~QMMEFP2 * ~QTPEFP2M * ~DMMBTCMF * ~DMMBT1BF * TBUFLAG then
  recovery = AC024H;

|**RECOVERY** ADGARC4Y 6.48E-01
elsif AMMDG3AF * ~QMMEFP2 * ~QTPEFP2M * ~DMMBTCMF * ~DMMBT1BF * TBUFLAG then
  recovery = ADGARC4Y;

|**RECOVERY** ADGBRC4Y 6.48E-01
elsif AMMDG3BF* ~QMMEFP2* ~QTPEFP2M* ~DMMBTCMF* ~DMMBT1BF* TBUFLAG then
  recovery = ADGBRC4Y;

|**RECOVERY** ADGARC4Y 6.48E-01
elsif ADGES3AM* ~QMMEFP2* ~QTPEFP2M* ~DMMBTCMF* ~DMMBT1BF* TBUFLAG then
  recovery = ADGARC4Y;

|**RECOVERY** ADGBRC4Y 6.48E-01
elsif ADGES3BM* ~QMMEFP2* ~QTPEFP2M* ~DMMBTCMF* ~DMMBT1BF* TBUFLAG then
  recovery = ADGBRC4Y;

|**RECOVERY** ADGARC1Y 9.07E-01
elsif AMMDG3AF* QMMEFP2* TBUFLAG then
  recovery = ADGARC1Y;
```

The recovery rule above searches through the core damage cut sets, first looking for any cut set containing the initiating event T3 and (a logical AND operation is signified by the "*") the basic event TBUFLAG (which is just a "flag" basic event) but not containing basic events QMMEFP2, QTPEFP2M, DMMBTCMF, and DMMBT1BF (the "~" indicates the event should not exist in the cut set). Cut sets meeting this first search criterion have the recovery action AC024H appended to the cut set. If a cut set does not meet the first search criterion, it is matched against the second search criterion, and this process is repeated until all cut sets have been evaluated.

Examining the rule above, it is evident that an analyst could not determine all possible combinations of basic events that could potentially come out of a PRA. The recovery rules that are used have been constructed based upon events in dominant cut sets from the dominant sequences. Consequently, for the dominant cut sets in the nominal case, the recovery rules are probably adequate. Also, for those nondominant cut sets that will be modified by an existing recovery rule, the recovery rules are probably adequate should the cut set become more likely in a particular configuration. But, for the nondominant cut sets that will not be modified by the existing recovery rules, the cut set frequency may be overestimated if an operator recovery is possible.

One way to identify the potential core damage frequency overestimation due to missing recovery actions is to partition the resulting cut sets into two groups. The first group would contain cut sets that have recovery actions applied to them. The second group would contain cut sets that do not have recovery actions applied to them. The cut sets listed in the second group would then be candidates for further scrutiny by the PRA analysts to determine the need for further recovery modeling. While this process of subdividing the cut sets into two groups could be readily accomplished using the IRRAS partition option or the R&R Workstation Cutset Editor, no investigations were performed as part of this study to determine the core damage frequency overestimation due to missing recovery actions. This impact on the core damage frequency is left for a future analysis. As part of this future analysis, it would be interesting to determine the applicability of the existing recovery rules to nondominant cut sets in addition to the impact of missing recovery actions.

Besides these issues, there is also the question of whether recovery action probabilities appropriately account for dependencies among the actions. This is an issue that is independent of the software package used to perform the analysis, because no software is known to currently allow the user to specify dependencies. Nor is it really desirable for the software package to automate this part of the analysis, as valuable insights could be missed if the analysts do not examine these dependencies carefully. Examining this issue is beyond the scope of the present report, but it is an issue that should be kept in mind whenever one is applying multiple recovery actions, particularly when using an automated, rule-based, engine.

5.0 Sensitivity to Truncation of Nominal Core Damage Results

Since the truncation level used in the Crystal River risk monitor and the IPE analyses was somewhat high (1E-8/yr), it was expected that changes to the cut set generation truncation level might have some effect on the PRA results. Consequently, these effects are investigated in this section. Specifically, the impacts on the cut sets and importance measures (e.g., Fussell-Vesely, Birnbaum, risk increase ratio) from changes in the cut set truncation level are explored. As part of the exploration, several items of interested were identified. First, changes in the overall core damage frequency and number of cut sets were evaluated. Second, changes in the values of several importance measures (e.g., Fussell-Vesely, risk increase ratio, and Birnbaum) were analyzed. And third, changes in the relative ranking of risk-important components were investigated.

For the evaluation of changes in the overall core damage frequency and cut sets, cut set generation was performed with truncation levels from 1E-7/yr to 1E-13/yr. The recovery rules were then applied to the generated cut sets. The results of these analyses are shown graphically below in Figure 3. As can be seen in the figure, as the truncation level is decreased, the total number of cut sets continues to increase even though the core damage frequency levels off (to a value of 1.3E-5/yr). The total number of cut sets is increasing by about a factor of six as the truncation level decreases by a factor of ten. Consequently, incorporating additional cut sets after a truncation level of 1E-10/yr to 1E-11/yr increases the core damage frequency negligibly.

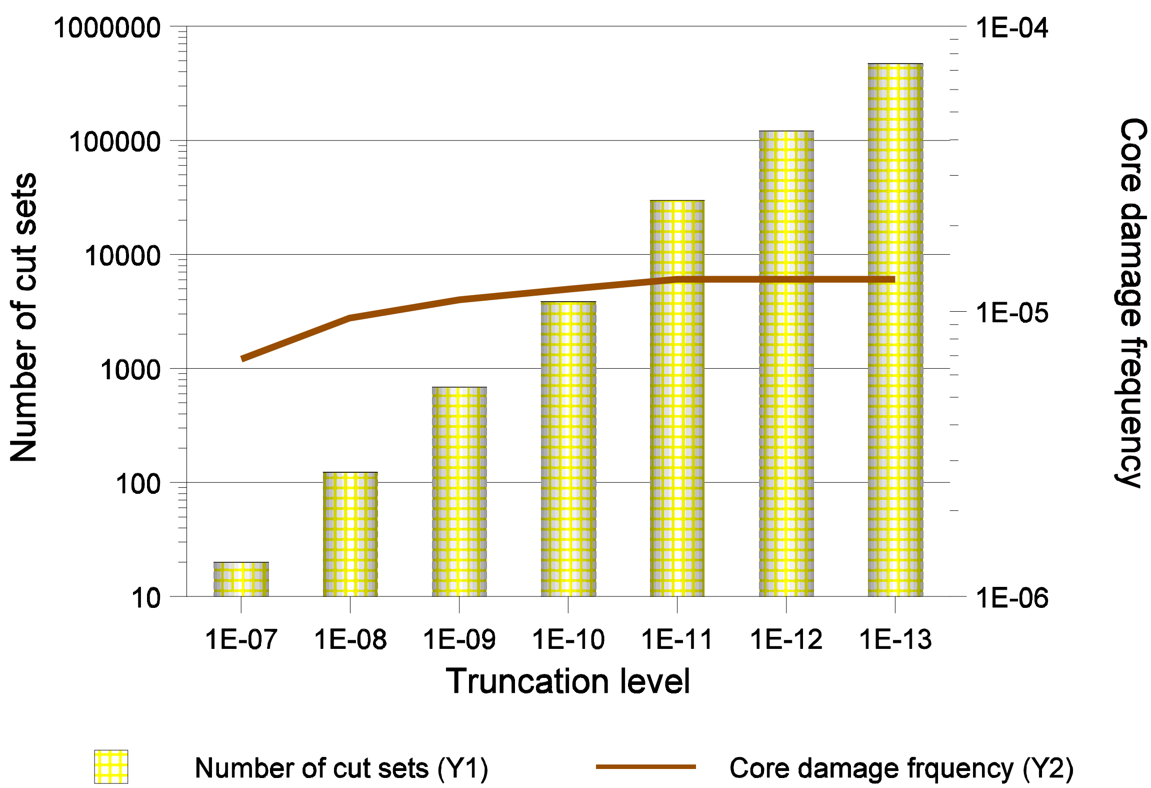

Figure 3. Sensitivity of the number of cut sets and core damage frequency for the Crystal River MLD to the cut set truncation level.

Figures 4 and 5 illustrate the Fussell-Vesely importance measures of a selected set of basic events for the nominal configuration. These Fussell-Vesely plots show that truncation level has a minor effect on the overall Fussell-Vesely values for the basic events. Some of the initiating event (e.g., S, small break LOCA and T3, loss of offsite power) Fussell-Vesely values decrease as the truncation level decreases. This decrease is caused by the generation of accident sequence cut sets for other types of initiating events. These additional cut sets will then cause the core damage frequency contribution to be reduced for the original dominant initiators. The largest absolute Fussell-Vesely change was found for basic event XHPR12H (operator fails to go to high pressure recirculation within 12 hours) which varied from 0.40 to 0.26.

Figures 6 and 7 illustrate the risk increase ratio of a selected set of basic events for the nominal configuration. These plots indicate that the risk increase ratio result for specific events can be affected by the truncation level of the cut set generation process. For many of the basic events, the risk increase ratio values are unaffected as the truncation level is lowered. But, the basic event LTKBWSTJ (representing failure of the borated water storage tank) has a significantly higher risk increase ratio value if the truncation level is less than 1E-8/yr. Note that for this event, the risk increase ratio changes from zero at a truncation of 1E-8/yr to about 1700 at a truncation of 1E-9/yr. In addition, at a truncation level of 1E-7/yr, a majority of the decay heat removal systems and related components do not have a risk increase ratio value because these events do not show up in the cutsets.

The Birnbaum graphs shown in Figures 8 and 9 display similar results with the basic event LTKBWSTJ having a significantly higher Birnbaum measure at truncation levels less than 1E-8/yr. In addition, many of the decay heat removal systems and related components do not register a significant Birnbaum importance measure when analyzed at a 1E-7/yr truncation level.

Figure 10 illustrates how the total number of "important" basic events (for the nominal case) changes as the truncation level is lowered. For this figure, the definition of what constitutes an "important" basic event is a basic event having an importance measure above the thresholds of either: Fussell-Vesely > 0.005, risk increase ratio > 2, and Birnbaum > 2E-5. As can be seen in the figure, the total number of events with Fussell-Vesely measures above 0.005 varies from about 30 to 70 as the truncation level is decreased. The risk increase ratio and Birnbaum events show a much larger change in the total number of events as the truncation level is varied. Both the risk increase ratio and Birnbaum measure show about 25 basic events above their respective thresholds at a 1E-7/yr truncation. But, at a truncation of 1E-10/yr, the total number of events above the thresholds increases to over 300. Thus, one must be very concerned with the truncation levels when performing risk-based inservice-testing and inservice-inspection analyses using PRA models. Use of PRA models for ranking components based upon importance measures could, in general, be sensitive to the truncation levels used for the analysis. Also, since PRA models typically split a components failure contribution into several individual basic event (e.g., fails to start, fails to run, common cause failure), the overall risk importance of the component may be underestimated if the individual events are analyzed seperately.

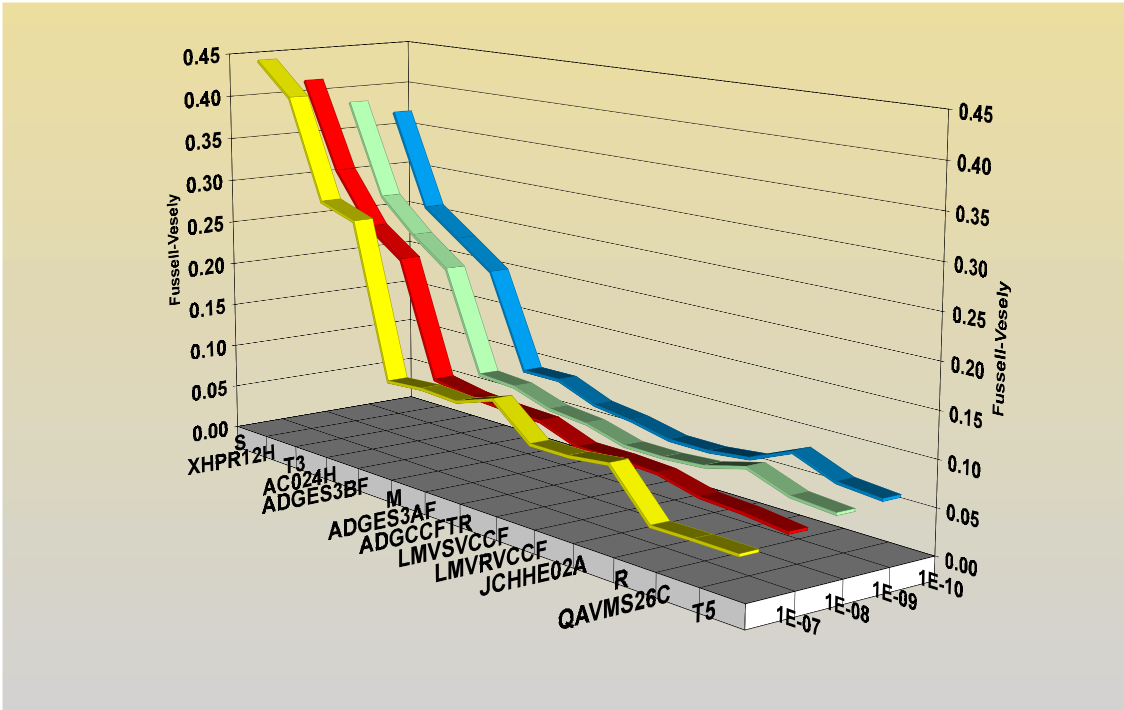

Figure 4. 3-D plot of base case Fussell-Vesely risk importance measure results.

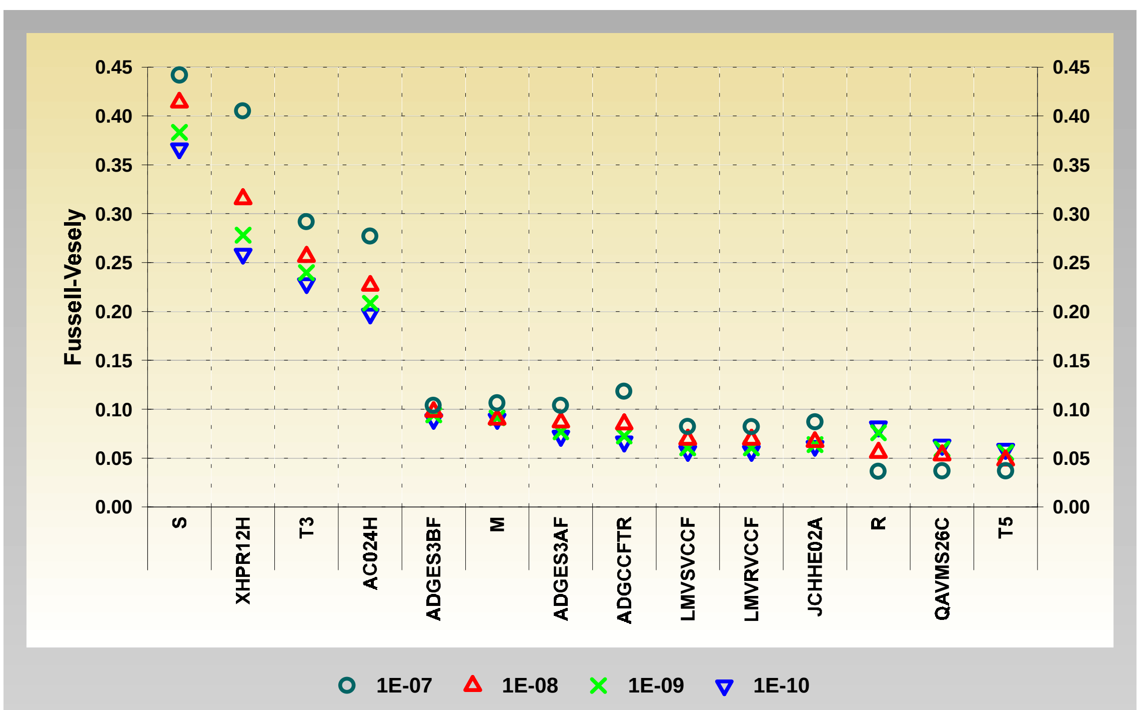

Figure 5. Scatter plot of base case Fussell-Vesely risk importance measure results.

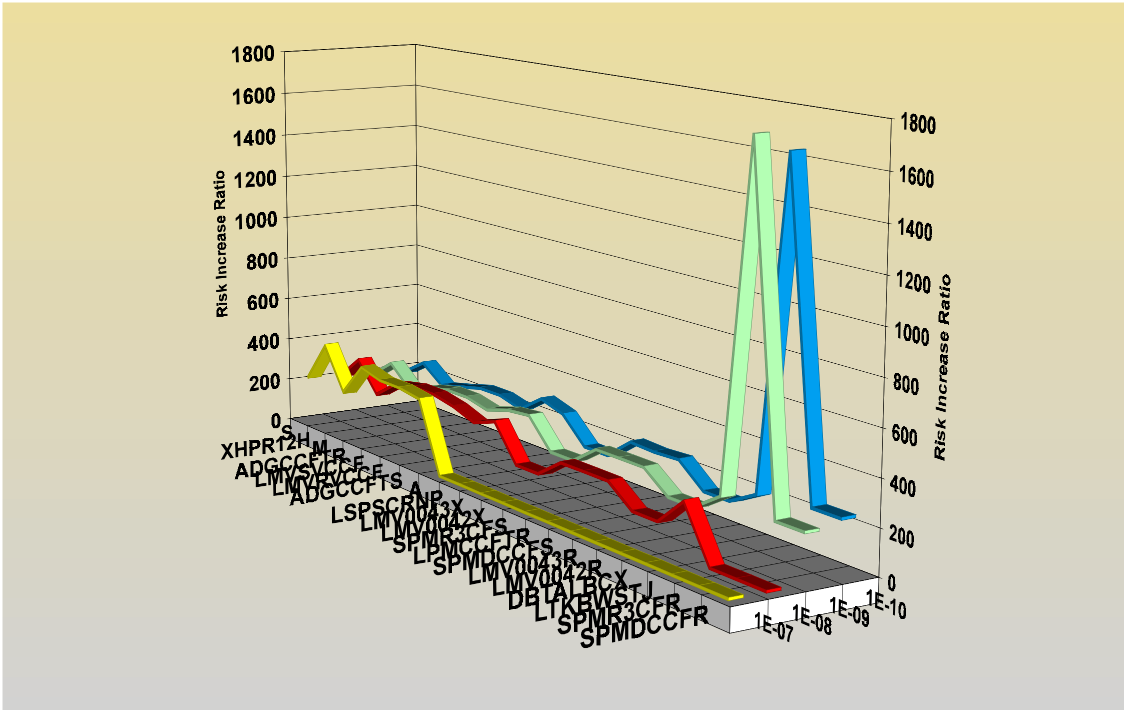

Figure 6. 3-D plot of base case risk increase ratio results.

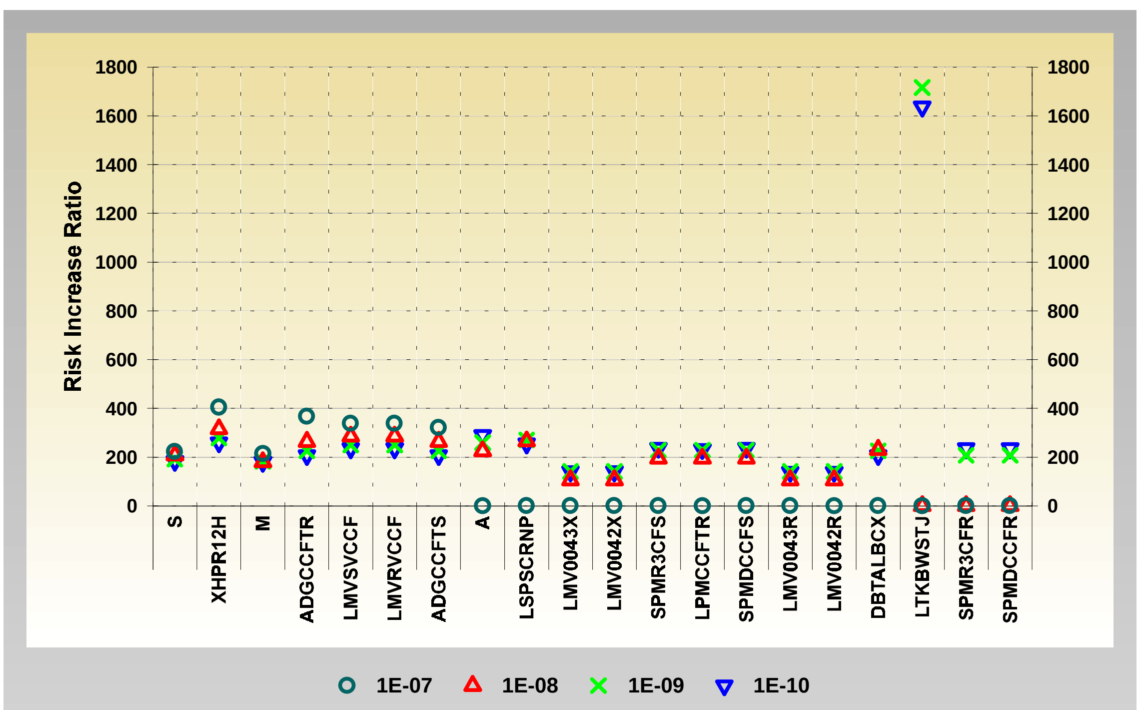

Figure 7. Scatter plot of base case risk increase ratio results.

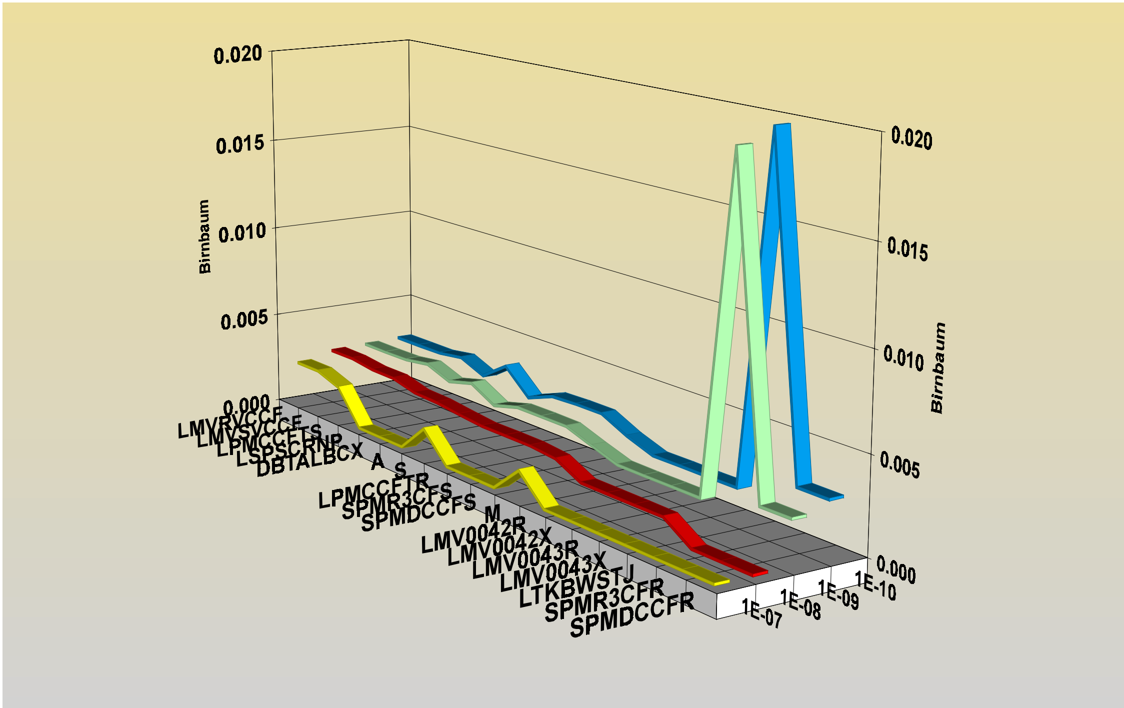

Figure 8. 3-D plot of base case Birnbaum risk importance measure.

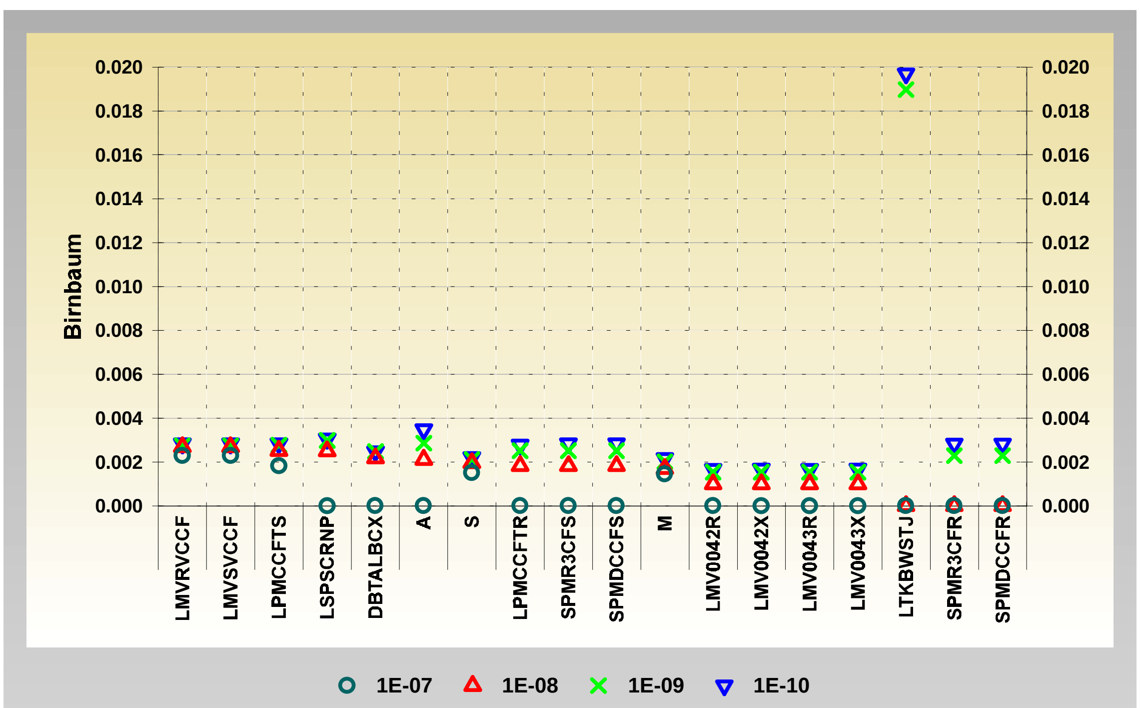

Figure 9 Scatter plot of base case Birnbaum risk importance measure.

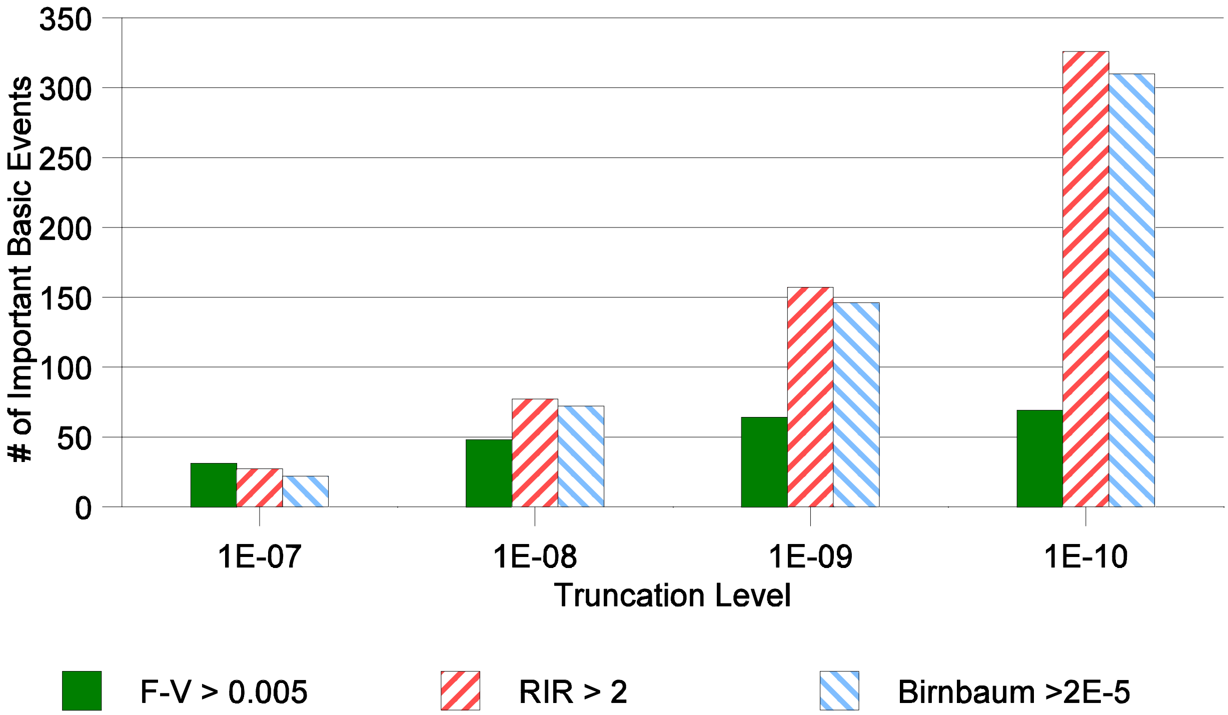

Figure 10. Sensitivity of the number of important basic events to the truncation level for the nominal configuration.

6.0 Core Damage Results for Important Configurations of Interest

After reviewing Crystal River operational records, BNL identified a total of 405 configurations of the plant (over the time period April 1 to September 30, 1995). Out of those 405 configurations, four interesting configurations (e.g., configurations with a range of high conditional core damage frequencies) were chosen for further investigations. These four configurations are:

Configuration 36 — Makeup motor-operated valves MUV-023 and MUV-024 inoperable with service water heat exchanger SWHE-1A inoperable.

Configuration 185 — Service water manual valves DCV-21 and DCV-25 inoperable

Configuration 221 — Reactor building spray motor-driven pump BP-1A inoperable, service water motor-driven pump DCP-1A inoperable, service water check valve RWV-38 inoperable, decay heat removal motor-driven pump DHP-1A inoperable, service water motor-driven pumps RWP-2A and RWP-3A inoperable, and service water filter RWSP-1A inoperable.

Configuration 295 — Makeup motor-driven pump MUP-1B inoperable with chiller CHHE-1A inoperable.

Once again, the SAPHIRE Crystal River plant risk model was used with IRRAS to obtain the overall conditional core damage frequency (both before and after applying recovery actions), uncertainty about the core damage frequency, dominant cut sets, and importance measures. The core damage frequency results are presented in Table 4 for the four configurations. These results were generated using a cut off level of 1E-8/yr. Tables 5 to 8 list a portion of the top cut sets that were generated for the four configurations at a 1E-8/yr truncation.

Table 4. Core damage frequency min-cut for four plant configurations (using 1E-8/yr truncation, before applying recovery rules).

Plant configuration	Core damage frequency (per year) before recovery rules are applied
36	6.1E-4
185	1.1E-4
221	1.8E-3
295	2.0E-3

Table 5. Top 14 cut sets from the Crystal River MLD (configuration 36, before recovery actions are applied).

#	Frequency/Event	Basic event description
1	1.162E-004	
	LUFLAG	HPI RECOVERY FLAG
	HMV0026N	MUV-26 FAILS TO OPEN
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407
2	1.162E-004	
	LUFLAG	HPI RECOVERY FLAG
	HMV0025N	MUV-25 FAILS TO OPEN
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407
3	1.063E-004	
	LUFLAG	HPI RECOVERY FLAG
	HMV0073N	MUV-73 FAILS TO OPEN ON DEMAND
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407
4	1.367E-005	
	LUFLAG	HPI RECOVERY FLAG
	HMV0025N	MUV-25 FAILS TO OPEN
	S	SMALL BREAK LOCA OCONEE IPE
5	1.367E-005	
	LUFLAG	HPI RECOVERY FLAG
	HMV0026N	MUV-26 FAILS TO OPEN
	S	SMALL BREAK LOCA OCONEE IPE
6	1.250E-005	
	LUFLAG	HPI RECOVERY FLAG
	HMV0073N	MUV-73 FAILS TO OPEN ON DEMAND
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	S	SMALL BREAK LOCA OCONEE IPE
7	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
8	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
9	8.132E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
10	8.132E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
11	6.927E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	QTPEFP2A	EFP-2 FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
12	6.009E-006	
	LUFLAG	HPI RECOVERY FLAG
	HMV0003K	MUV-3 TRANSFERS CLOSED SP-347
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407
13	5.235E-006	
	LUFLAG	HPI RECOVERY FLAG
	HCV0037N	MUV-37 FAILS TO OPEN
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407
14	5.235E-006	
	LUFLAG	HPI RECOVERY FLAG
	HCV0036N	MUV-36 FAILS TO OPEN
	R	STEAM GENERATOR TUBE RUPTURE NUREG/CR-4407

Table 6. Top 14 cut sets from the Crystal River MLD (configuration 185, before recovery actions are applied).

#	Frequency/Event	Basic event description
1	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
2	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
3	8.132E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
4	8.132E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
5	4.445E-006	
	ADGCCFTS	EDG CCF TO START NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
6	4.445E-006	
	ADGCCFTS	EDG CCF TO START NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
7	3.223E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
8	3.223E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BA	EDG-3B FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
9	3.223E-006	
	ADGES3AA	EDG-3A FAILS TO START
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
10	3.223E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
11	2.000E-006	
	XFLAG	HPR RECOVERY FLAG
	XHPR12H	OPERATOR FAILS TO GO TO HPR (12H) HRA
	S	SMALL BREAK LOCA OCONEE IPE
12	1.713E-006	
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	T8	LOSS OF 4160V ES BUS 3A IE
	TBUFLAG	TBU RECOVERY FLAG
13	1.713E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
14	1.713E-006	
	ADGES3AF	EDG-3A FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
	TBUFLAG	TBU RECOVERY FLAG

Table 7. Top 13 cut sets from the Crystal River MLD (configuration 221, before recovery actions are applied).

#	Frequency/Event	Basic event description
1	4.879E-004	
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
2	4.879E-004	
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
3	1.934E-004	
	ADGES3BA	EDG-3B FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
4	1.934E-004	
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
5	1.027E-004	
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
6	1.027E-004	
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
7	1.280E-005	
	ACB3210C	BREAKER FAILS TO CLOSE
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
8	1.280E-005	
	ACB3210C	BREAKER FAILS TO CLOSE
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
9	1.250E-005	
	LMV0043N	DHV-43 FAILS TO OPEN
	XFLAG	HPR RECOVERY FLAG
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	S	SMALL BREAK LOCA OCONEE IPE
10	1.250E-005	
	LMVDV12N	DHV-12 FAILS TO OPEN
	XFLAG	HPR RECOVERY FLAG
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	S	SMALL BREAK LOCA OCONEE IPE
11	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
12	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
13	8.269E-006	
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	HOPINJBY	OPERATOR FAILS TO SWITCH MUV-25/26 TO BACKUP POWER HRA
	TBUFLAG	TBU RECOVERY FLAG

Table 8. Top 14 cut sets from the Crystal River MLD (configuration 295, before recovery actions are applied).

#	Frequency/Event	Basic event description
1	5.335E-004	
	ADGES3BF	EDG-3B FAILS TO RUN
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
2	4.879E-004	
	ADGES3BF	EDG-3B FAILS TO RUN
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
3	2.115E-004	
	ADGES3BA	EDG-3B FAILS TO START
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
4	1.934E-004	
	ADGES3BA	EDG-3B FAILS TO START
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
5	1.123E-004	
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
6	1.027E-004	
	T3	LOSS OF OFFSITE POWER IE
	T9	LOSS OF 4160V ES BUS 3B IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
7	5.072E-005	
	PAFWH	CREW FAILS TO START AFW IN 15 MIN. HRA
	XFLAG	HPR RECOVERY FLAG
	T9	LOSS OF 4160V ES BUS 3B IE
8	4.638E-005	
	PAFWH	CREW FAILS TO START AFW IN 15 MIN. HRA
	T9	LOSS OF 4160V ES BUS 3B IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
9	3.210E-005	
	XFLAG	HPR RECOVERY FLAG
	T9	LOSS OF 4160V ES BUS 3B IE
	PMSTTF	TURBINE FAILS TO TRIP GIVEN REACTOR TRIP SCREENING
10	2.936E-005	
	T9	LOSS OF 4160V ES BUS 3B IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
	PMSTTF	TURBINE FAILS TO TRIP GIVEN REACTOR TRIP SCREENING
11	1.400E-005	
	ACB3210C	BREAKER FAILS TO CLOSE
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE
12	1.280E-005	
	ACB3210C	BREAKER FAILS TO CLOSE
	T3	LOSS OF OFFSITE POWER IE
	HNOMAINT	NO MAKEUP PUMPS IN MAINTENANCE 1-M.U.
	TBUFLAG	TBU RECOVERY FLAG
13	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	T3	LOSS OF OFFSITE POWER IE
	TBUFLAG	TBU RECOVERY FLAG
14	1.130E-005	
	ADGCCFTR	EDG CCF TO RUN NUREG-1150
	XFLAG	HPR RECOVERY FLAG
	T3	LOSS OF OFFSITE POWER IE

The core damage cut sets for each configuration were generated by (1) using the nominal probabilities for basic events not modeled as inoperable for the configuration, (2) setting testing and maintenance events to a zero probability, and (3) setting basic events for inoperable components to a probability of 1.0 (via a logical TRUE setting). As part of the risk profile analysis conducted by BNL, the BNL researchers set the common-cause basic events associated with the inoperable components to a probability of 0.0 (via a logical FALSE setting). The practice of setting common-cause failure basic events to FALSE is explored in a latter section of this report. The actual basic event data changes that were used for each of the analyzed plant configurations are shown in Table 9.

The effects of recovery actions and truncation levels on the results for these four configurations are explored in the following sections.

Table 9. Basic event data changed for each analyzed plant configuration.

Configuration	Basic event	Basic event value for configuration
36	HMV0023K	TRUE
	HMV0023N	TRUE
	HMV0023X	TRUE
	HMV0024K	TRUE
	HMV0024N	TRUE
	HMV0024X	TRUE
	SHXHE1AM	TRUE
	SHXSW1AF	TRUE
185	SXVDC21K	TRUE
	SXVDC21N	TRUE
	SXVDC25K	TRUE
	SXVDC25N	TRUE
221	IPMBP1AA	TRUE
	IPMBP1AF	TRUE
	IPMBSPAM	TRUE
	SPMDP1AA	TRUE
	SPMDP1AF	TRUE
	SPMDHCAM	TRUE
	SPMDHCAX	TRUE
	SPMDCCFR	FALSE
	SPMDCCFS	FALSE
	SCVRW38C	FALSE
	SCVRW38N	TRUE
	LPM001AA	TRUE
	LPM001AF	TRUE
	LPM001AM	TRUE
	LPMCCFTR	FALSE
	LPMCCFTS	FALSE
	SPMRW2AA	TRUE
	SPMRW2AF	TRUE
	SPMRW2AM	TRUE
	SPMRW2AX	TRUE
	SPMR2CFR	FALSE
	SPMR2CFS	FALSE
	SPMR3CFR	FALSE
	SPMR3CFS	FALSE
	SPMRW3AA	TRUE
	SPMRW3AF	TRUE
	SPMRW3AM	TRUE
	SPMRW3AX	TRUE
	SFLRSPAP	TRUE
295	HPM001BA	TRUE
	HPM001BF	TRUE
	HPM001BM	TRUE
	WPMWD5BA	TRUE
	WPMWD5BF	TRUE
	JCHHE1AF	TRUE
	JCHCCFTF	FALSE

7.0 Effects of Recovery Actions on Important Configurations

As discussed for the nominal case results, we are only interested in the impact on cut sets due to the application of recovery actions on the cut sets generated from the logic model. We are not interested in the overall impact of the removal of impossible cut sets or cut sets with mutually exclusive events. But, as indicated for the nominal core damage results, the removal of impossible cut sets or cut sets with mutually exclusive events has a smaller effect on the core damage frequency when compared to the application of recovery actions. Thus, the sensitivity cases described in this section will illustrate the overall effect of applying the recovery rules (i.e., both removal of events and appending recovery actions) to the generated cut sets for each configuration of interest.

For the sensitivity analyses, cut sets were generated using the MLD at truncation levels of 1E-8/yr and 1E-10/yr. The core damage frequency results of these sensitivity analyses are shown in Table 10, while the number of generated cut sets is shown in Table 11.

Table 10. Sensitivity evaluation results for effect of recovery actions on overall core damage frequency.

Configuration	Core damage frequency (per year) *before* recovery rules are applied		Core damage frequency (per year) *after* recovery rules are applied	
	1E-8 truncation	1E-10 truncation	1E-8 truncation	1E-10 truncation
36	6.1E-4	6.3E-4	4.6E-4	4.7E-4
185	1.1E-4	1.2E-4	9.9E-6	1.3E-5
221	1.8E-3	1.8E-3	1.4E-4	1.5E-4
295	2.0E-3	2.0E-3	3.0E-4	3.1E-4

Table 11. Sensitivity evaluation results for effect of recovery actions on total number of generated cut sets.

Configuration	Total number of generated cut sets *before* recovery rules are applied		Total number of generated cut sets *after* recovery rules are applied	
	1E-8 truncation	1E-10 truncation	1E-8 truncation	1E-10 truncation
36	1,071	21,020	427	11,067
185	446	9,588	141	4,158
221	808	15,441	451	8,698
295	1,002	15,605	652	11,274

Once again, we can see from looking at Table 10 that the *truncation level* has little impact on the core damage frequency for the cases of before- or after-applying recovery rules. But, *applying the recovery rules* does have an effect on both the core damage frequency and the total number of cut sets that are generated.

For configuration 36, the core damage frequency is slightly reduced by the application of the recovery rules (from 6.3E-4/yr to 4.7E-4/yr). This small decrease in core damage frequency may imply that the cut sets that are dominant for this particular sequence either (1) are not candidates for removal or recovery or (2) are candidates for removal or recovery, but are not affected by the current recovery rules since the cut sets were originally nondominant. Recovery rules are typically not designed to affect nondominant cut sets. For configuration 36, the recovery rules that are utilized eliminate almost half of the original generated cut sets.

The sensitivity analyses for configurations 185, 221, and 295 show similar results. Applying the recovery rules reduces the core damage frequency by an order of magnitude. This order of magnitude reduction is similar to the reduction found for the nominal core damage frequency results. Once again, for each configuration, the total number of cut sets is cut in half by the application of the recovery rules.

8.0 Sensitivity to Truncation of Important Configurations

Sensitivity analyses were performed for each of the important configurations. The results of these analyses are divided into configuration 36, 185, 221, and 295 subsections, respectively. These configuration analyses were performed using truncation levels of 1E-7 to 1E-10. For the analyses, several truncation issues were explored, including: changes in core damage frequency and number of generated cut sets, affects on overall uncertainty, and impacts on the numeric value and ranking of importance measures.

Configuration 36

The total number of cut sets and the core damage frequency for configuration 36 are plotted in Figure 11 as a function of the truncation level. These plotted results are for the case where the recovery rules have already been applied.

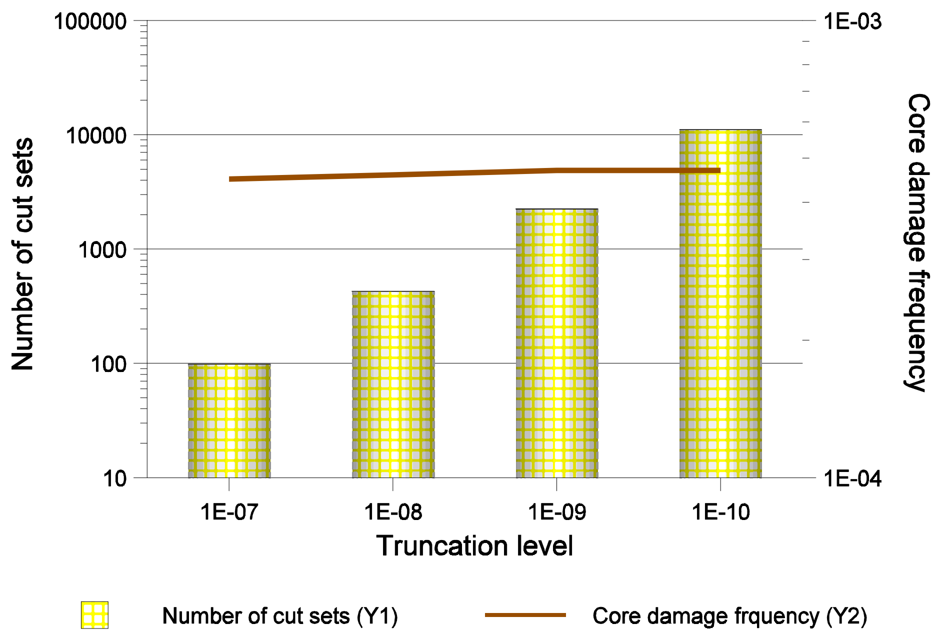

Figure 11. Sensitivity of the number of cut sets and core damage frequency for configuration 36 to the truncation level.

Figures 12 and 13 illustrate the Fussell-Vesely risk importance measures for configuration 36. The results indicated that for the various truncation levels, the Fussell-Vesely values are similar. Figures 14 and 15 are the risk increase ratio results. These ratio plots indicate that as the truncation level decreases, the risk increase ratio generally increases. For example, basic event ARO311AF has a risk increase ratio of 35 at a truncation level of 1E-7/yr while it has a risk increase ratio of 52 at a truncation level of 1E-10/yr. The Birnbaum plots shown in Figures 16 and 17 show similiar results.

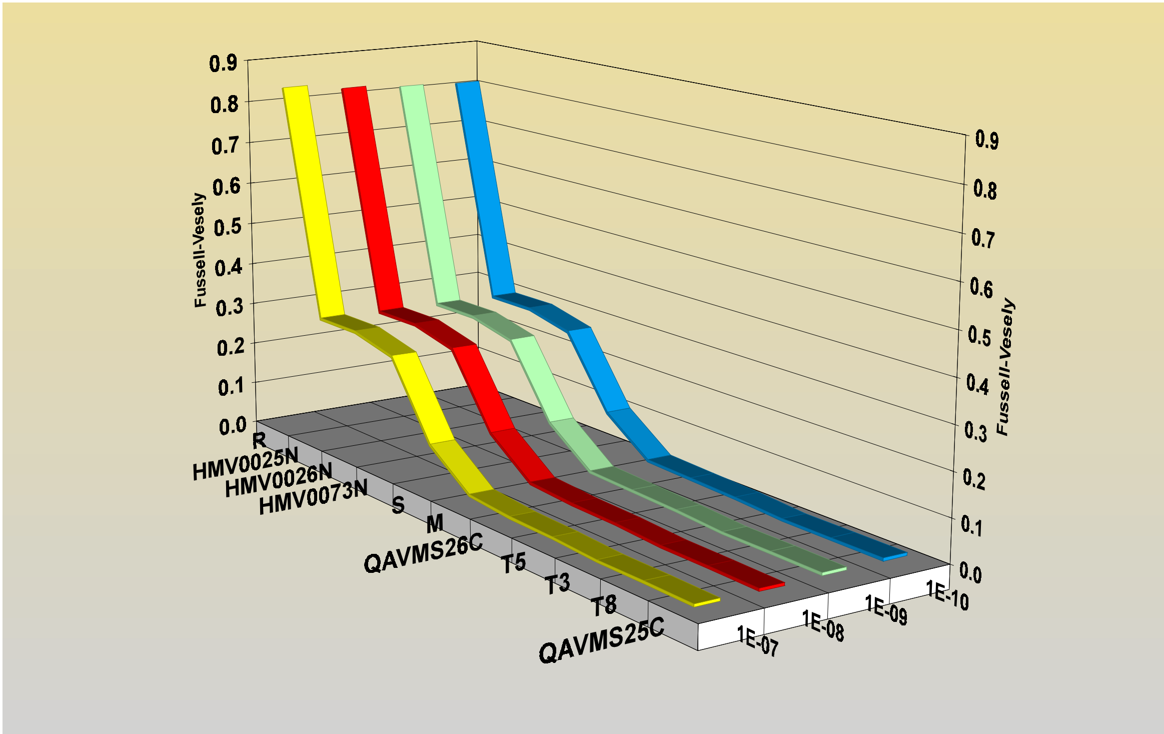

Figure 12. 3-D plot of configuration 36 Fussell-Vesely importance measure results.

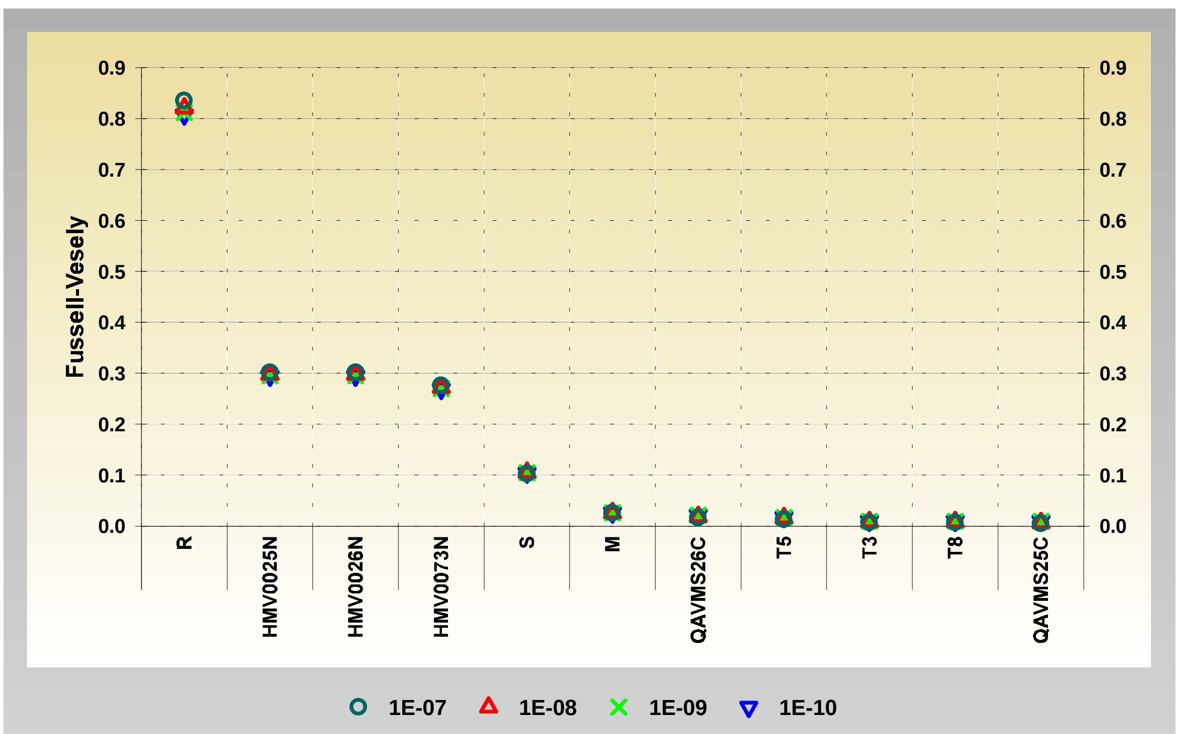

Figure 13. Scatter plot of configuration 36 Fussell-Vesely importance measure results.

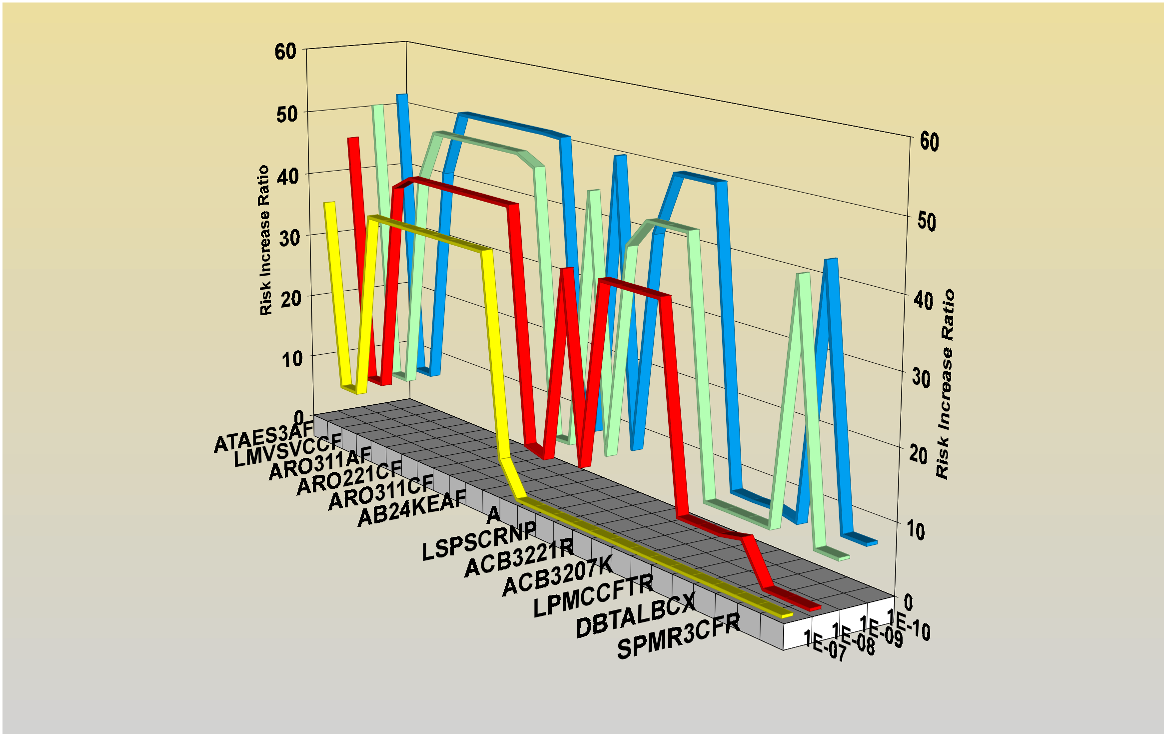

Figure 14. 3-D plot of configuration 36 risk increase ratio results.

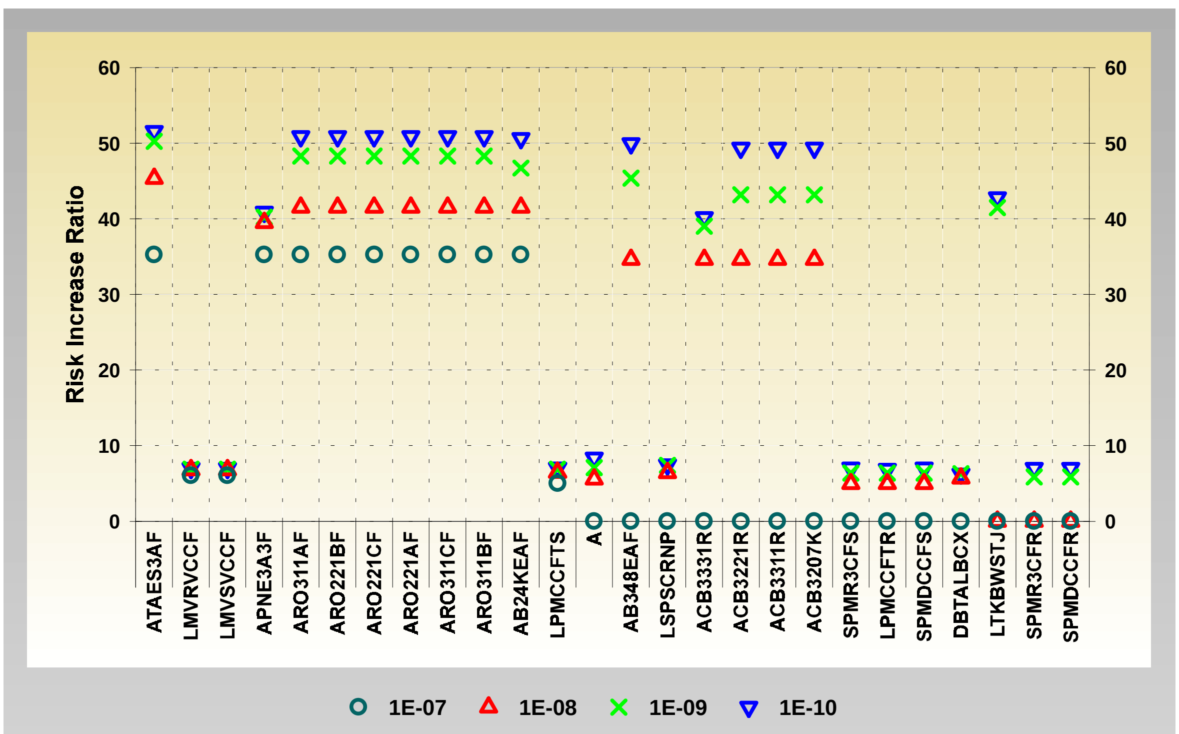

Figure 15. Scatter plot of configuration 36 risk increase ratio results.

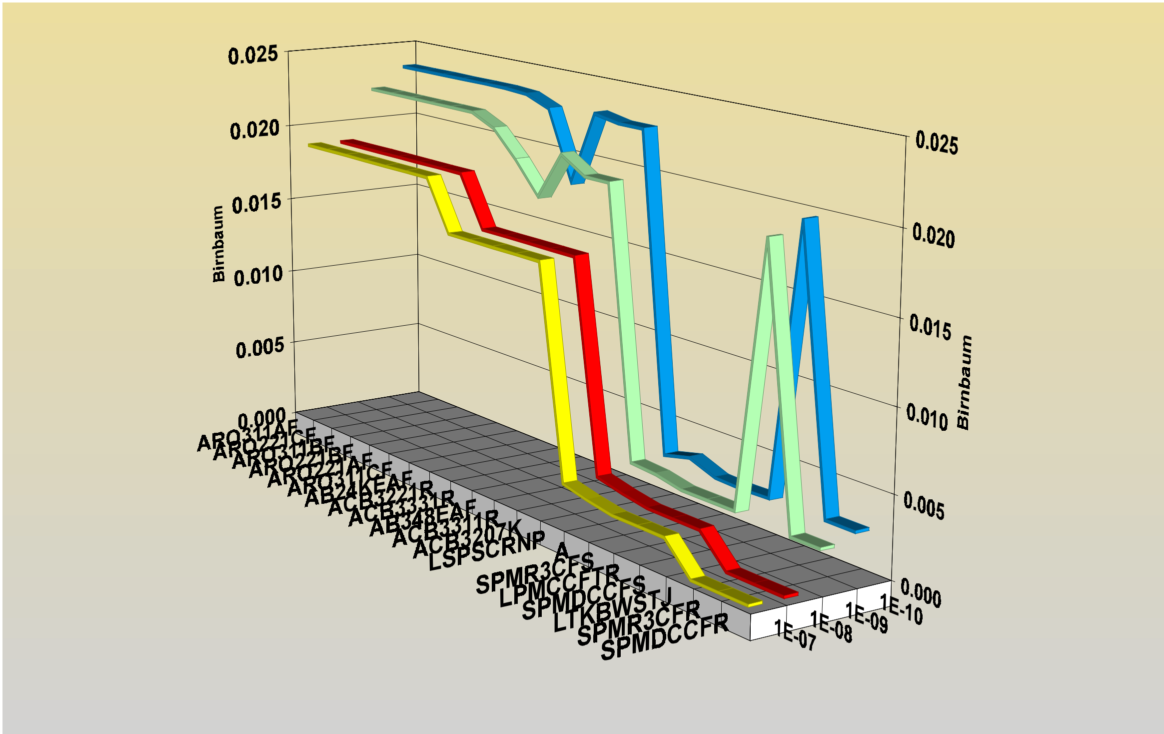

Figure 16. 3-D plot of configuration 36 Birnbaum importance measure results.

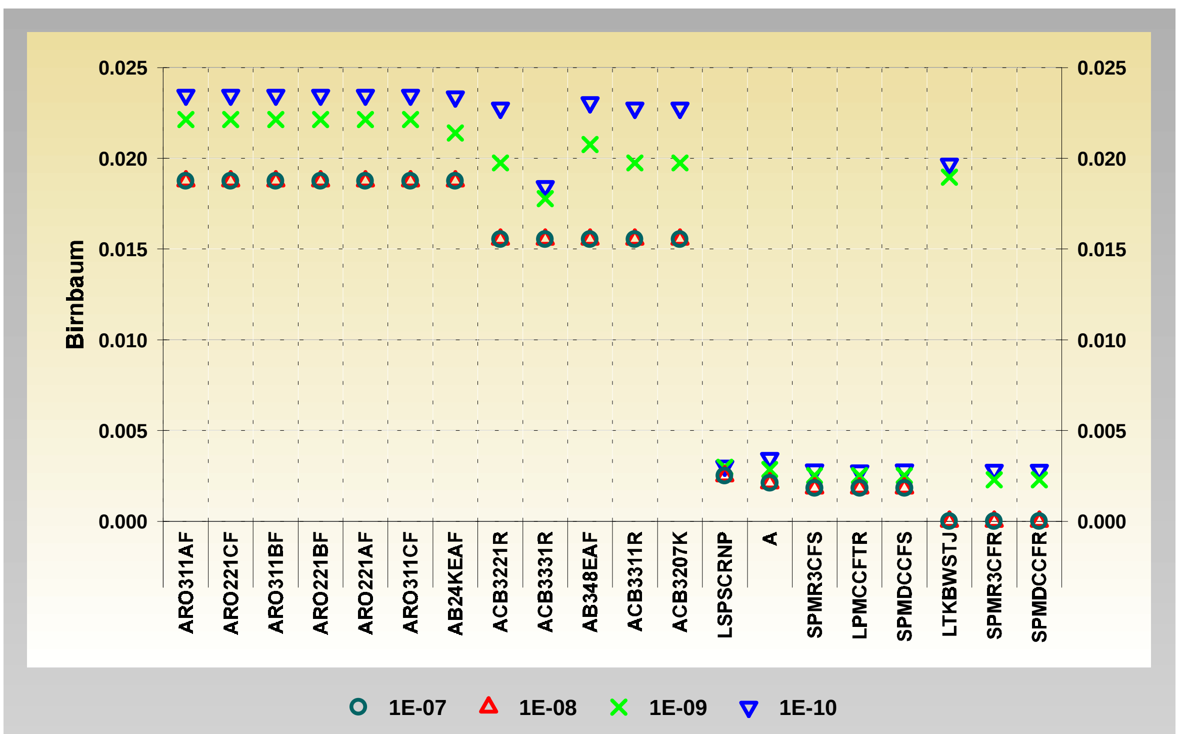

Figure 17. Scatter plot of configuration 36 Birnbaum importance measure results.

Since some risk-based applications use importance measures as a basic event or component ranking tool, the sensitivity of basic event importance to truncation level may be of interest. Consequently, for the cut sets generated using the truncation levels of 1E-7/yr to 1E-10/yr, a list of important components were developed. A component was defined as being "important" if it met the following criteria:

Fussell-Vesely importance measure > 0.005

Risk increase ratio measure > 2

Birnbaum importance measure > 2E-5

The total number of components that were identified as being important was determined for each truncation level. A plot of the number of important basic events is shown in Figure 18. As can be seen in the figure, the total number of basic events as defined by the Fussell-Vesely criterion varies little as the truncation level is lowered. However, the number of important basic events as defined by the Birnbaum and risk increase ratio measures does increase as the truncation is lowered. For example, about 150 basic events are "important" as defined by the Birnbaum criterion for a truncation of 1E-7/yr, but the number of events jumps to 500 at a truncation of 1E-10/yr. Thus, one should be aware of the sensitivity of the importance measures to truncation levels.

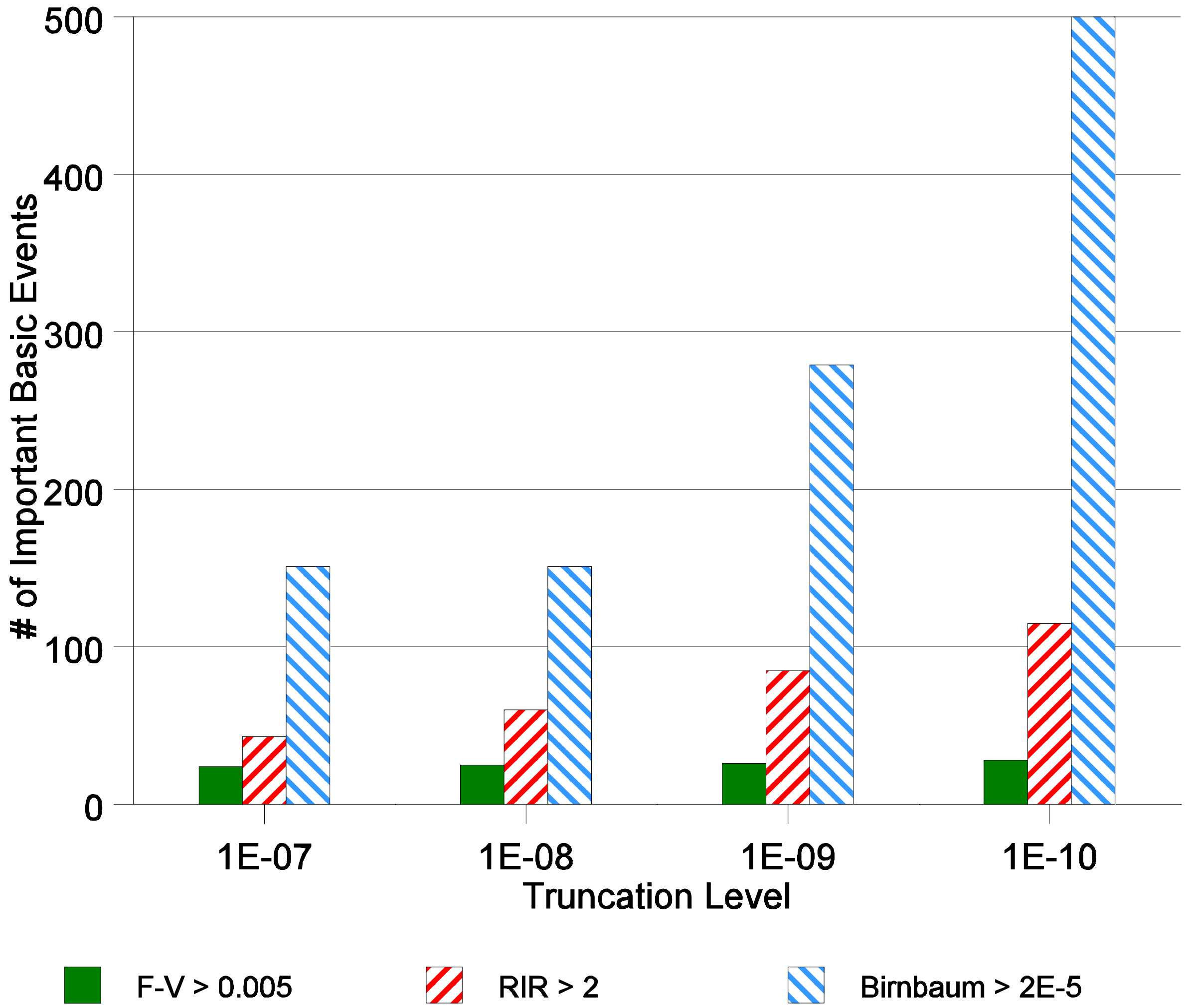

Figure 18. Sensitivity of the number of important basic events to the truncation level for configuration 36.

Configuration 185

The total number of cut sets and the core damage frequency for configuration 185 are plotted in Figure 19 as a function of the truncation level. These plotted results are for the case where the recovery rules have already been applied.

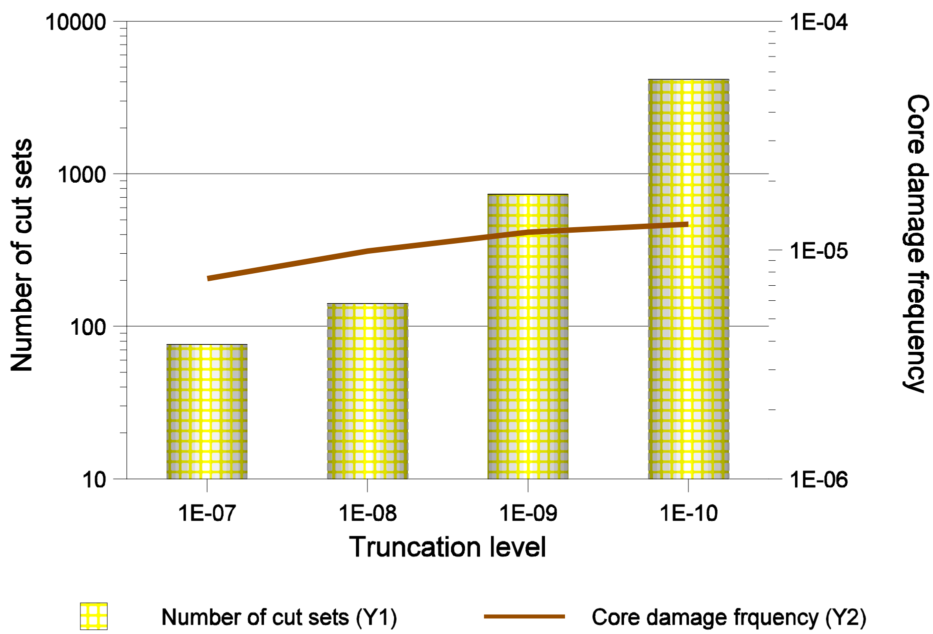

Figure 19. Sensitivity of the number of cut sets and core damage frequency for configuration 185 to the truncation level.

Figures 20 and 21 illustrate the Fussell-Vesely importance measures for configuration 185. As in the base case, the most significant events in terms of the Fussell-Vesely risk importance measure are the initiating events for a small LOCA and the loss of offsite power, as well as basic events XHPR12H (operator fails to go to high pressure recirculation) and AC024H (offsite power not restored). Truncation levels appear to have only a small effect on the Fussell-Vesely values for the basic events. Figures 22 and 23 show of the risk increase ratio for configuration 185 while Figures 24 and 25 the Birnbaum risk importance measures These plots indicate that the risk increase ratio value for specific events can be affected by the truncation level. Both the ratio and the Birnbaum measures results reveal that the basic event representing the borated water storage tank failure (LTKBWSJ) has a significantly higher measure at truncation levels lower than 1E-8/yr. In addition, at a truncation level of 1E-7/yr, many of the decay heat removal systems and support systems such as LPMCCFTR (decay heat pump CCF to run), SPMDCCFS [decay heat cooling pump common cause failure (CCF) to start], and SPMR3CFR (raw water pump CCF to run) do not have a risk increase ratio or Birnbaum value (because these events do not show up in the cut sets) when compared to the other truncation levels. Figure 26 shows the sensitivity of the number of important basic events as a function of the truncation level.

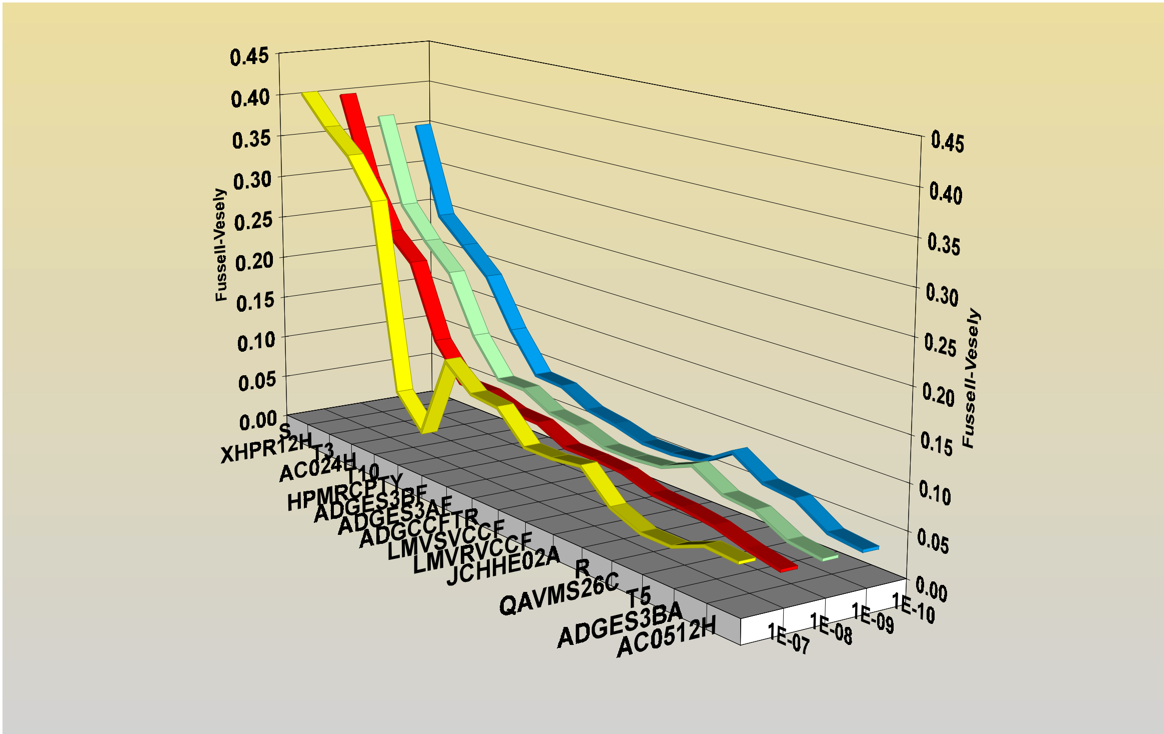

Figure 20. 3-D plot of configuration 185 Fussell-Vesely importance measure results.

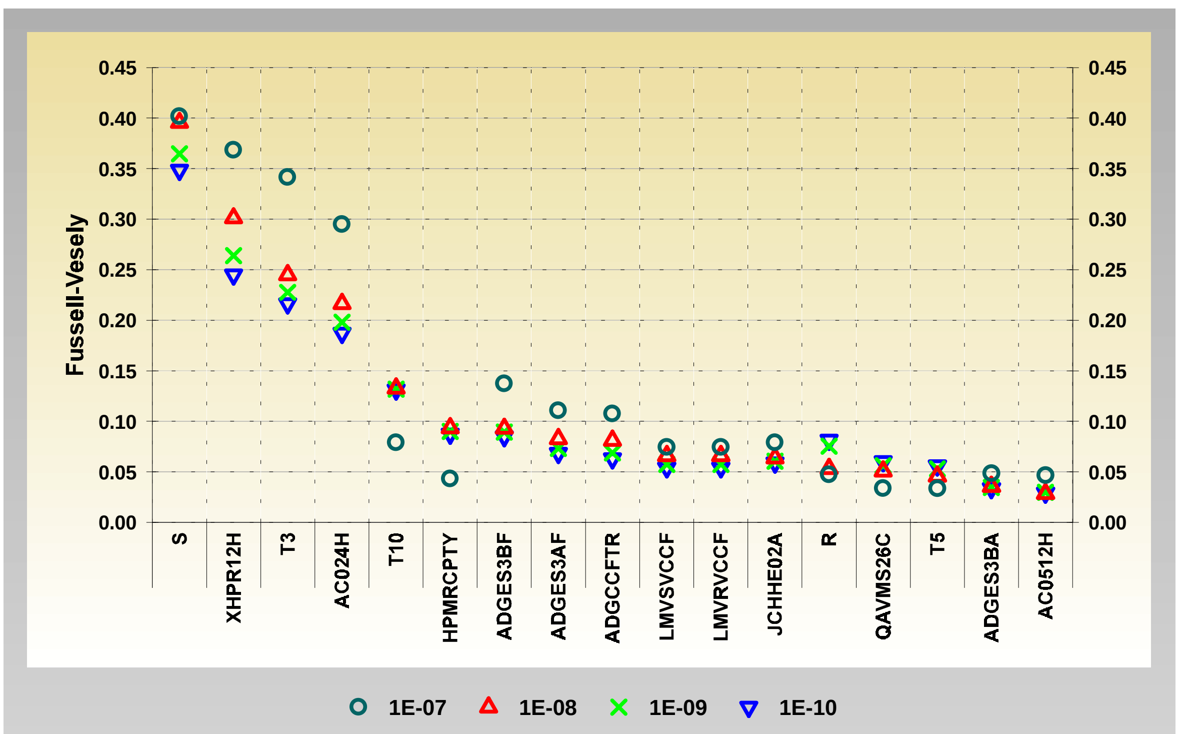

Figure 21. Scatter plot of configuration 185 Fussell-Vesely importance measure results.

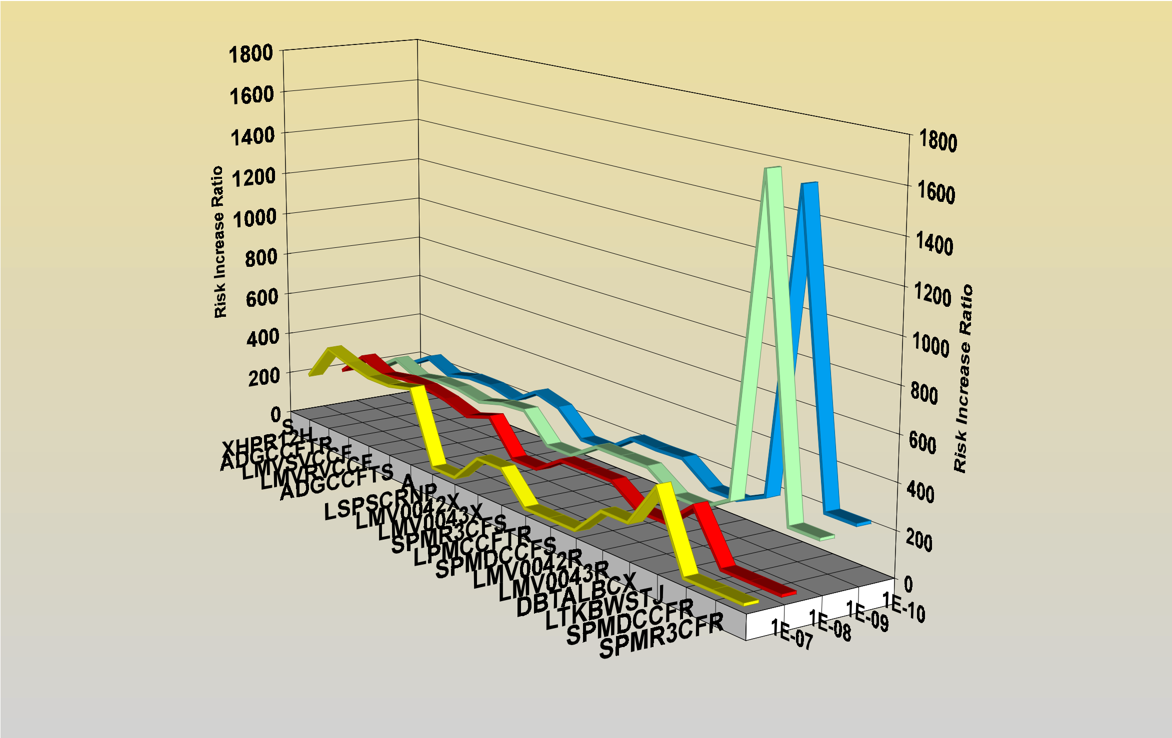

Figure 22. 3-D plot of configuration 185 risk increase ratio results.

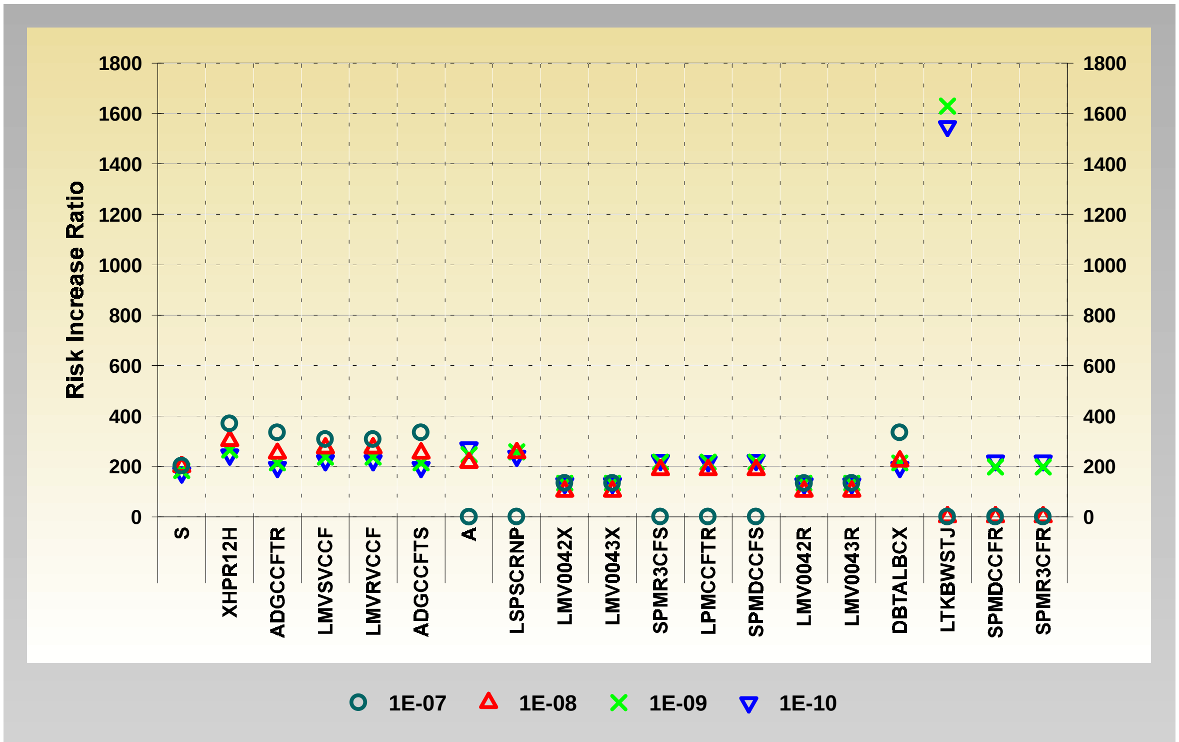

Figure 23. Scatter plot of configuration 185 risk increase ratio results.

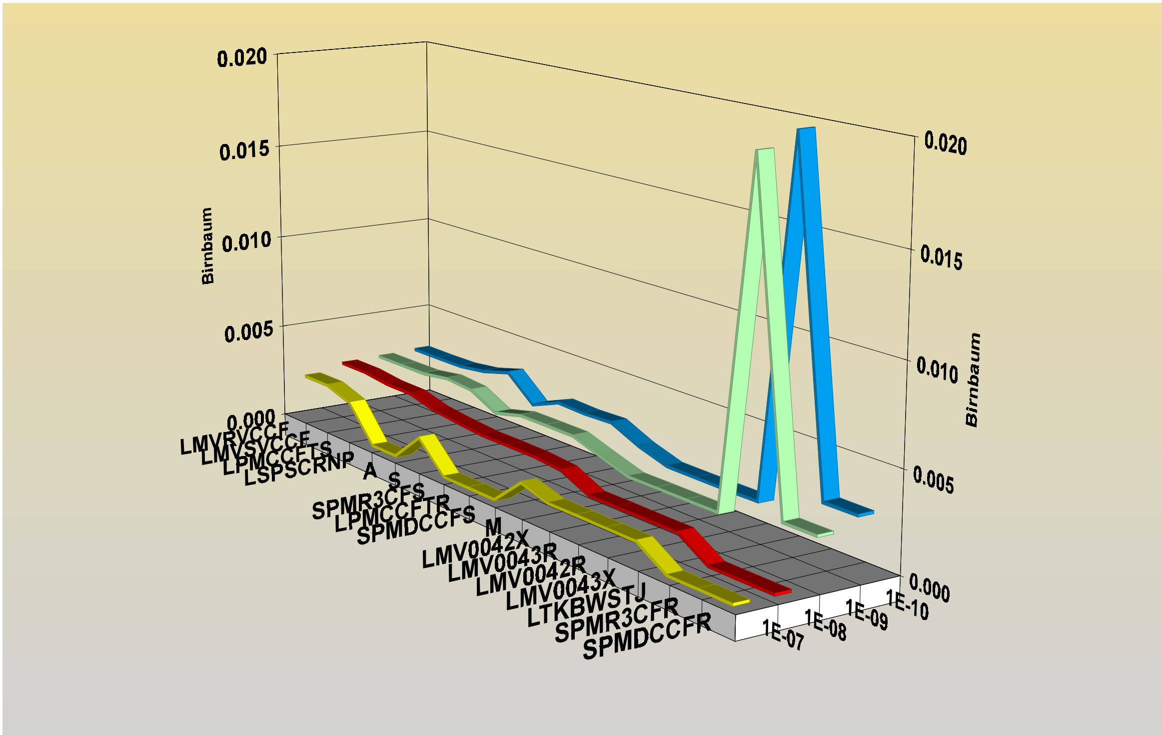

Figure 24. 3-D plot of configuration 185 Birnbaum risk importance measure results.

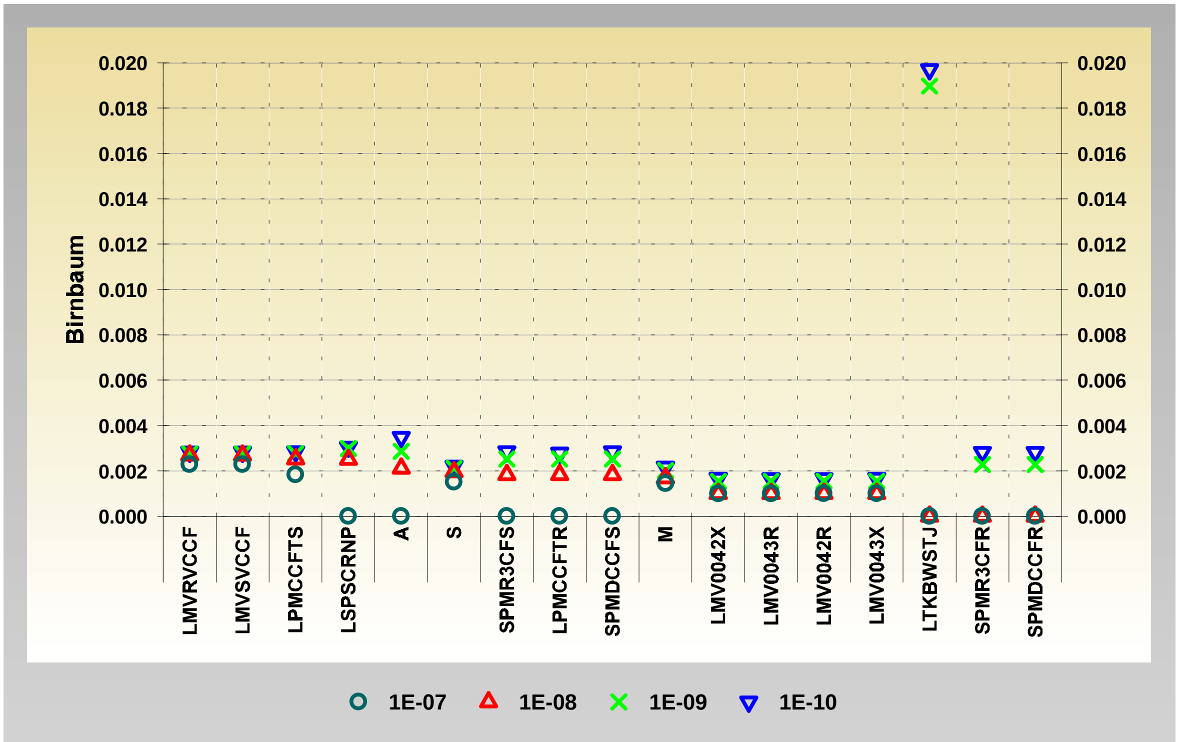

Figure 25. Scatter plot of configuration 185 Birnbaum risk importance measure results.

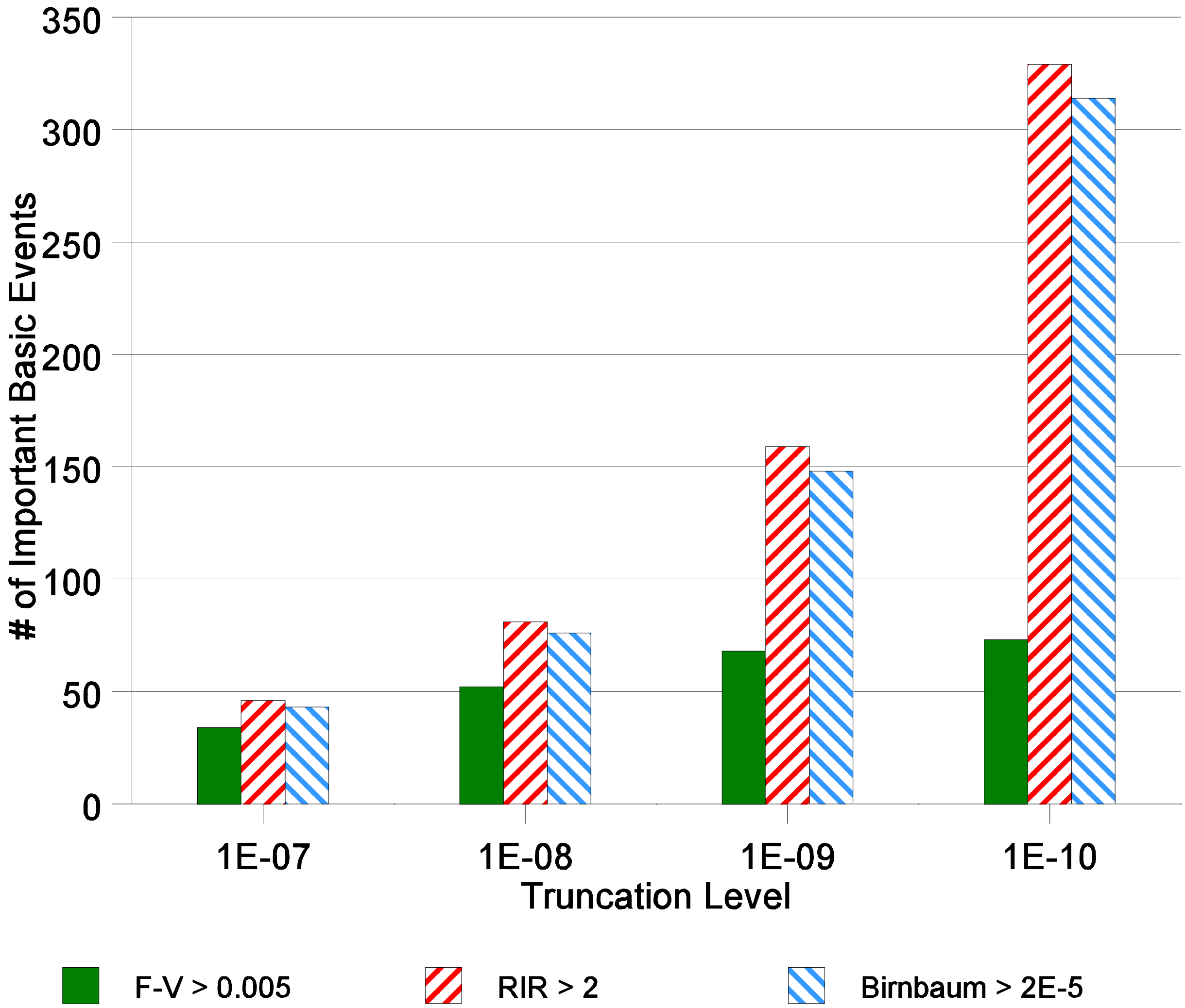

Figure 26. Sensitivity of the number of important basic events to truncation level for configuration 185.

As part of the "after recovery" analyses for configuration 185, the parameter uncertainties for the basic events were propagated through the model using Monte Carlo sampling. This uncertainty analysis was performed at several truncation levels to see if truncation had any effect on the overall uncertainty. A total of 10,000 iterations was performed at each truncation level. The overall results of the uncertainty analysis are shown in Figure 27.

As can been seen in Figure 27, the uncertainty results change little as the truncation level is reduced. The mean and percentiles do increase slightly as the truncation level is decreased. Also, the overall "spread" (i.e., the distance between the 95th and 5th percentiles) of the upper and lower bounds decreases as the truncation level is decreased. For example, the ratio of the 95th to 5th percentile changes from 48 to 26 for the 1E-7/yr to 1E-10/yr truncation levels, respectively.

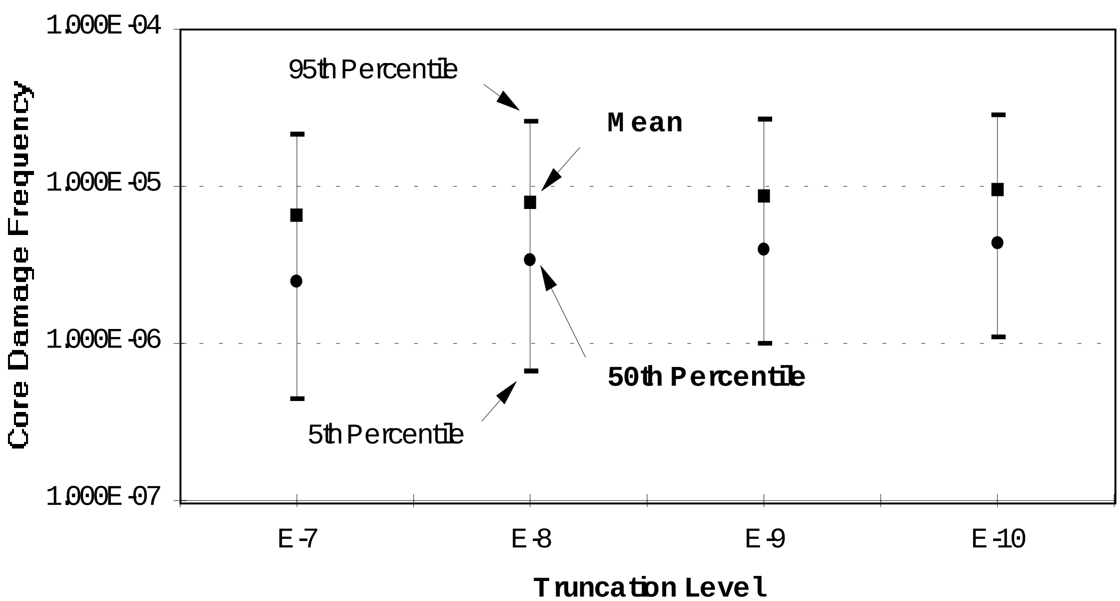

Figure 27. Sensitivity of core damage frequency uncertainty to truncation level for configuration 185.

Configuration 221

The total number of cut sets and the core damage frequency for configuration 221 are plotted in Figure 28 as a function of the truncation level. These plotted results are for the case where the recovery rules have already been applied.

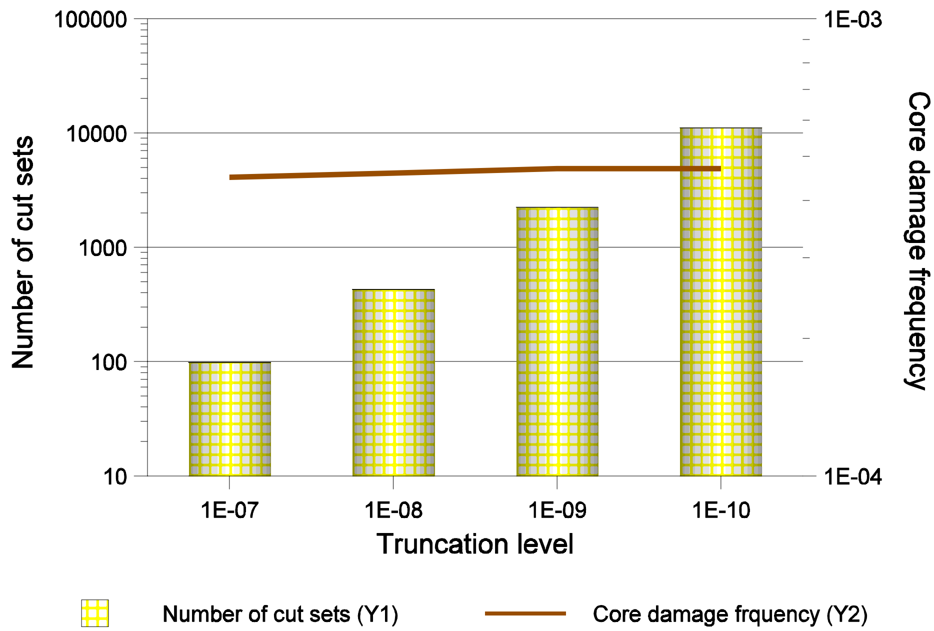

Figure 28. Sensitivity of the number of cut sets and core damage frequency for configuration 221 to the truncation level.

Figures 29 and 30 illustrate the Fussell-Vesely importance measure results for configuration 221. The plots for the various truncation levels follow similar patterns with very small deviations between levels. Figures 31 and 32 represent the risk increase ratio for configuration 221. The truncation levels produced similar risk increase ratio results except for basic event ACB3208K (breaker transfers close), which has a low risk increase ratio value at a truncation level of 1E-7/yr that increases to about 110 at a truncation level of 1E-8/yr. Basic event LTKBWSTJ (borated water storage tank failure) shows a low risk increase ratio value at 1E-7/yr and 1E-8/yr but this value increases to 130 at truncation levels of 1E-9/yr and 1E-10/yr. Similar results for these events are observed for the Birnbaum results and are shown in Figures 33 and 34. Figure 35 shows the sensitivity of the number of important basic events to truncation level.

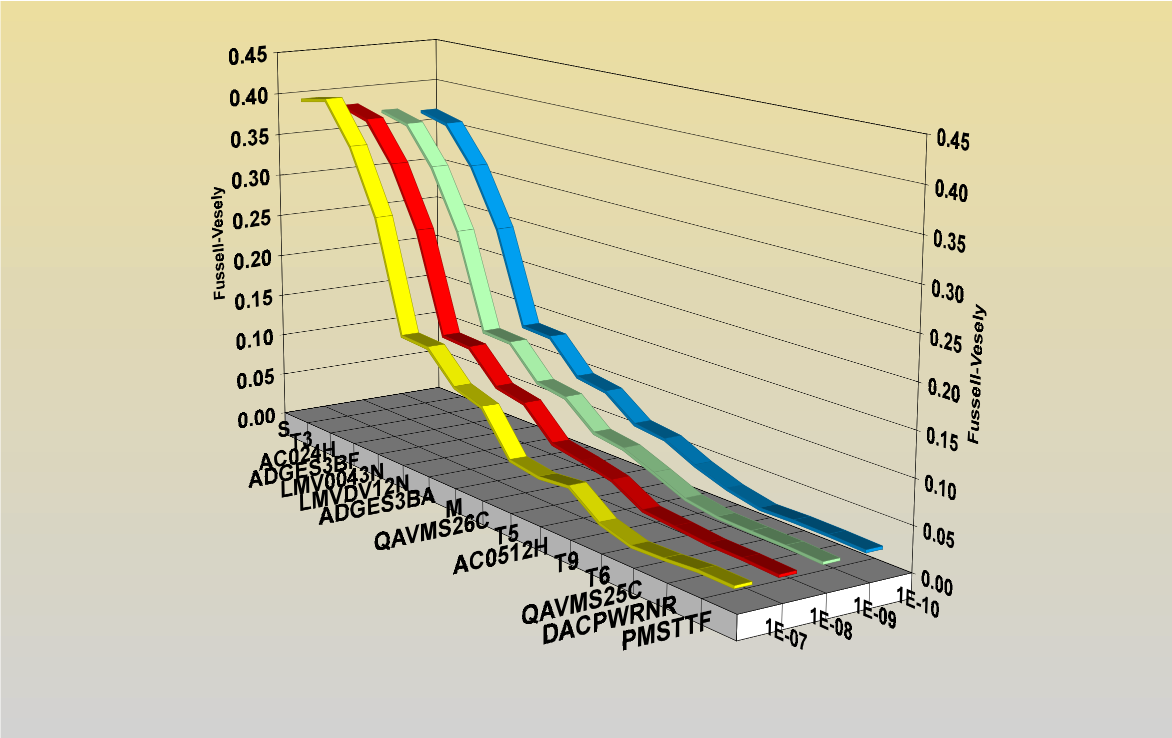

Figure 29. 3-D plot of configuration 221 Fussell-Vesely importance measure results.

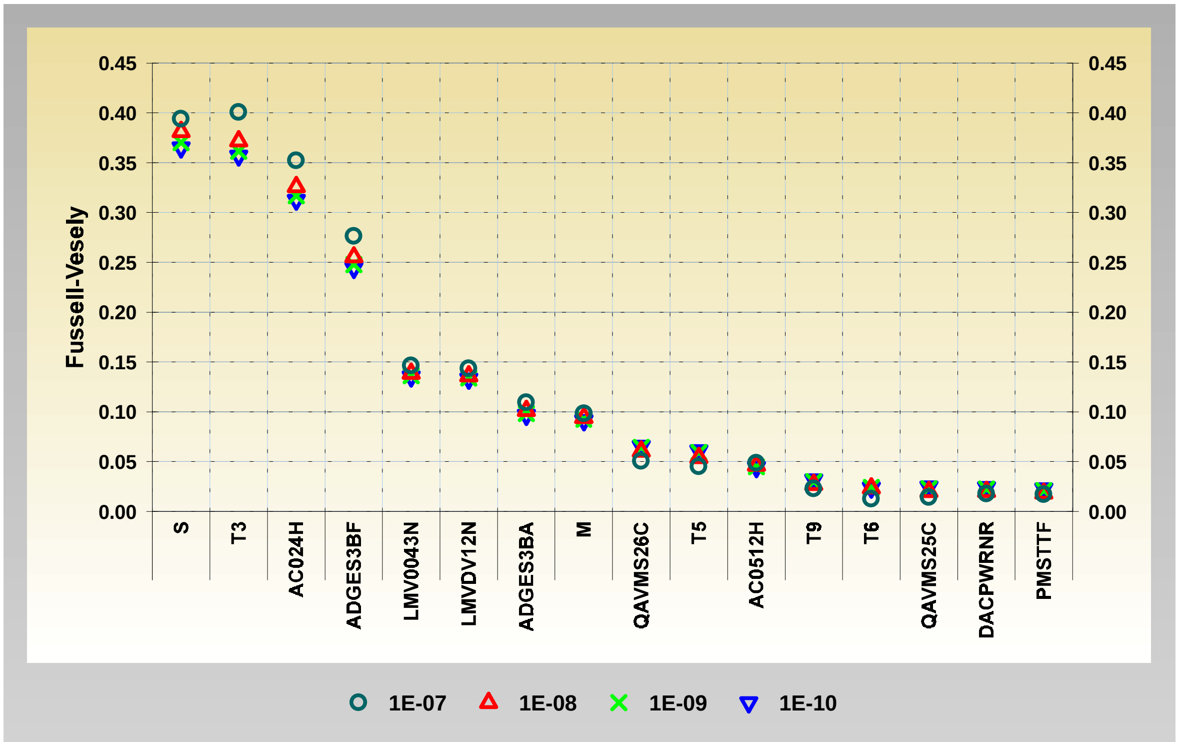

Figure 30. Scatter plot of configuration 221 Fussell-Vesely importance measure results.

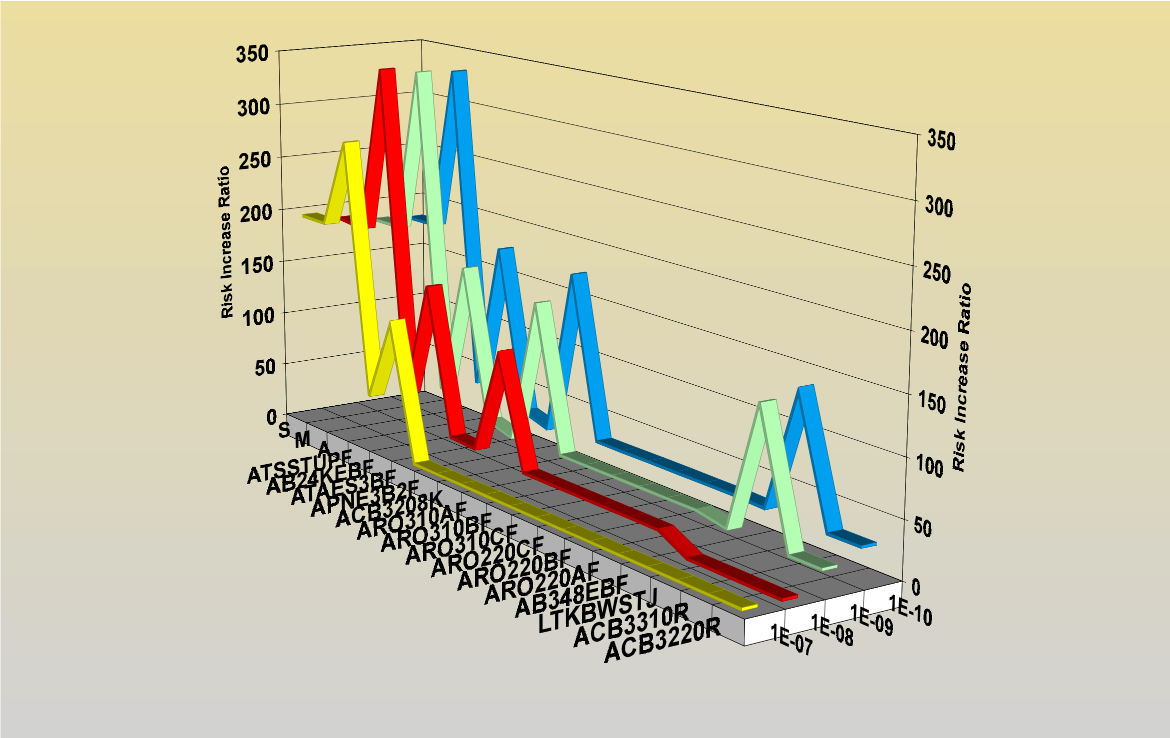

Figure 31. 3-D plot of configuration 221 risk increase ratio results.

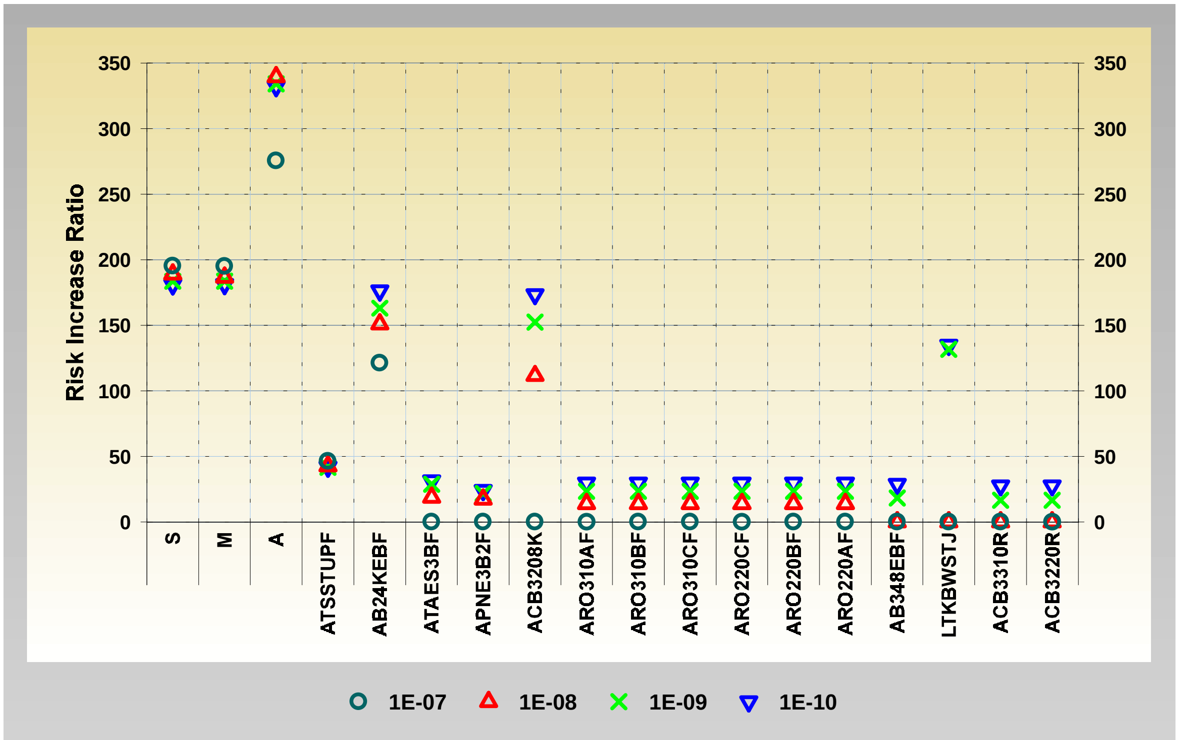

Figure 32. Scatter plot of configuration 221 risk increase ratio results.

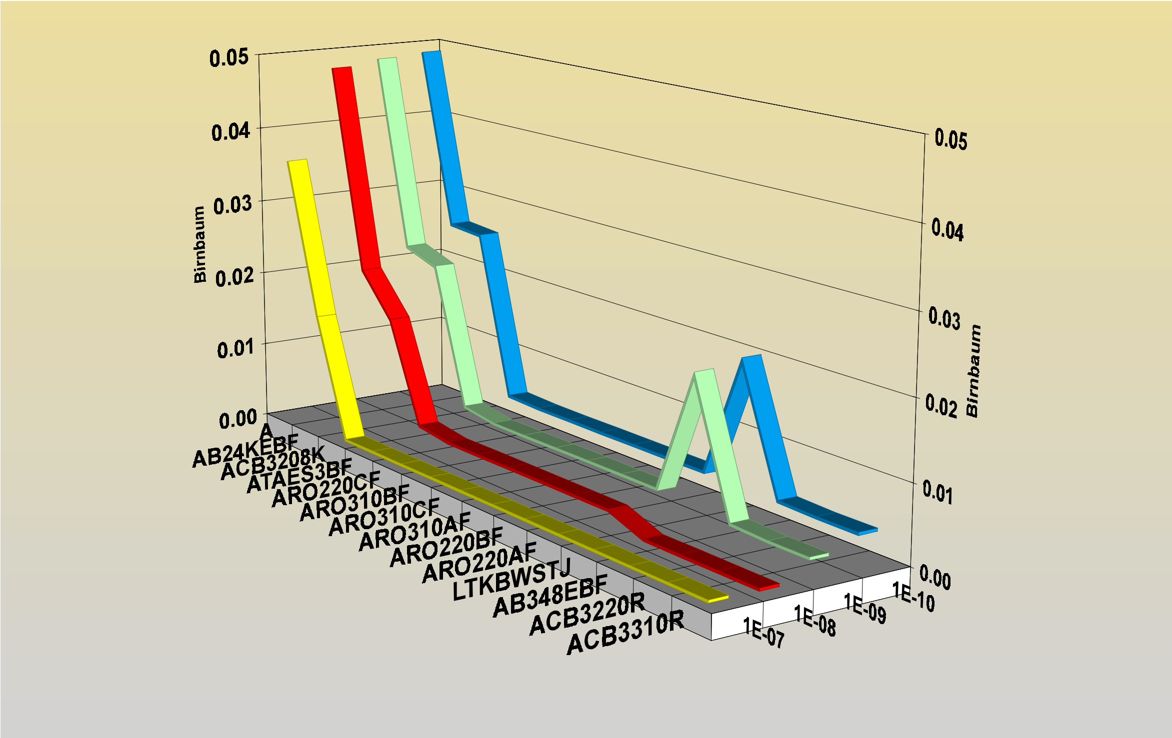

Figure 33. 3-D plot of configuration 221 Birnbaum risk importance measure results.

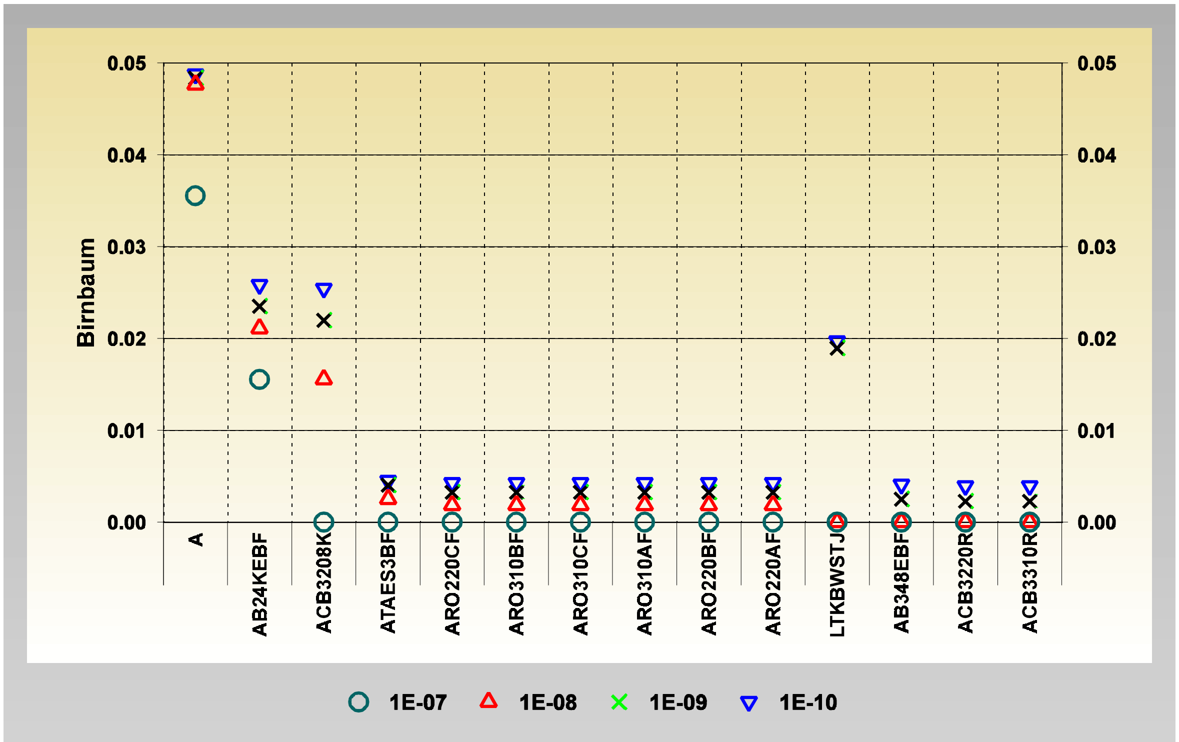

Figure 34. Scatter plot of configuration 221 Birnbaum risk importance measure results.

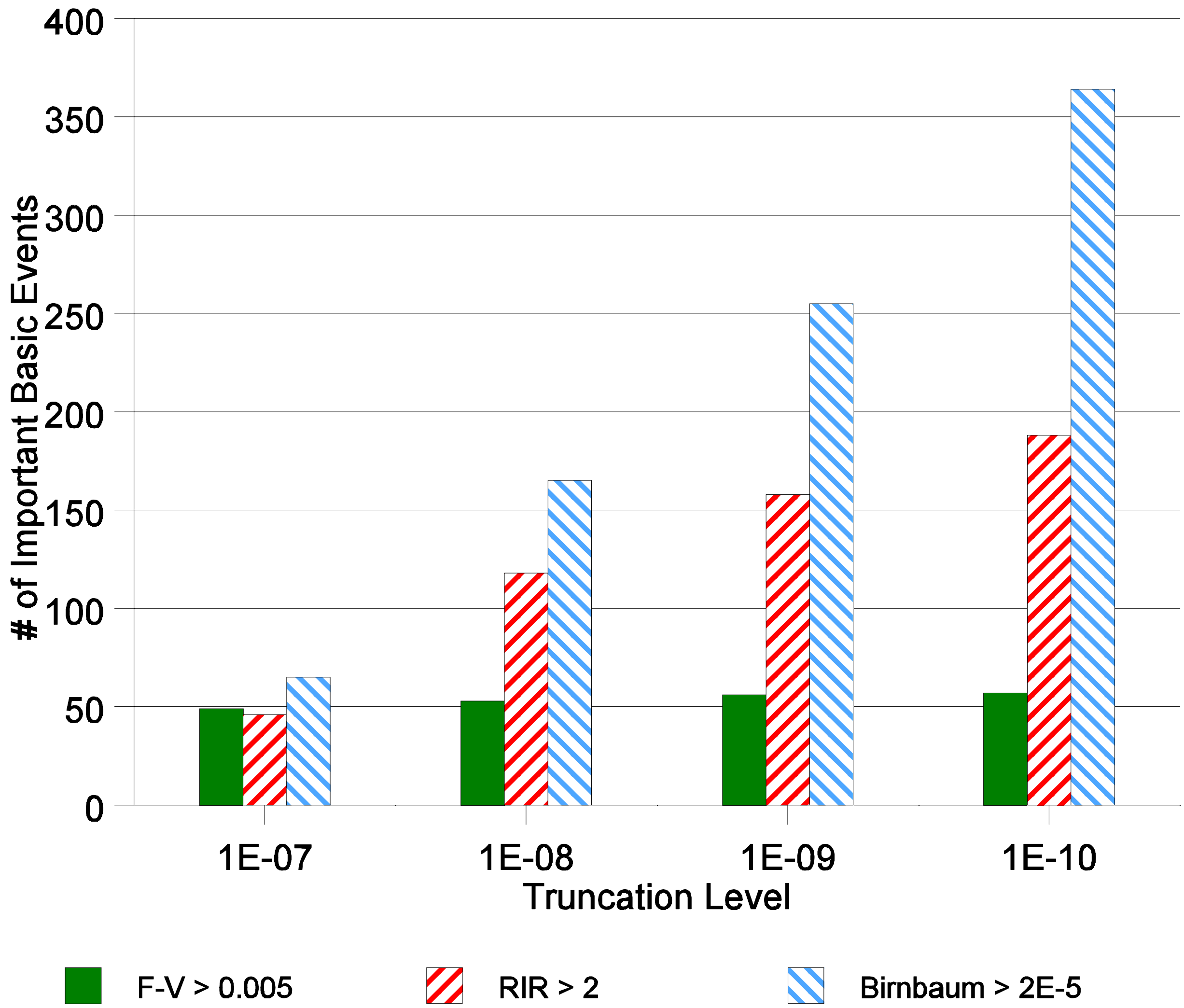

Figure 35. Sensitivity of the number of important basic events to truncation level for configuration 221.

Configuration 295

The total number of cut sets and the core damage frequency for configuration 295 are plotted in Figure 36 as a function of the truncation level. These plotted results are for the case where the recovery rules have already been applied.

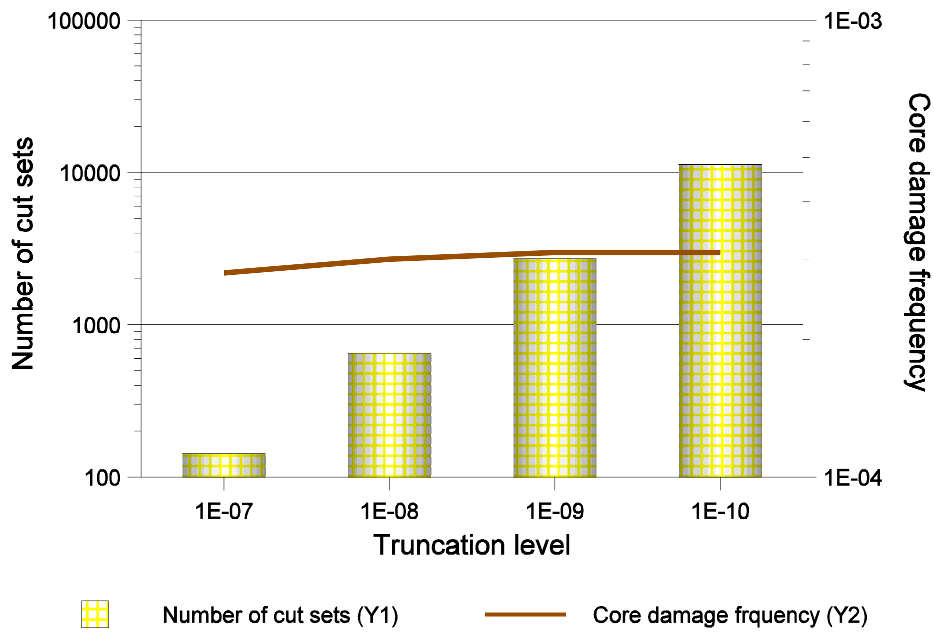

Figure 36. Sensitivity of the number of cut sets and core damage frequency for configuration 295 to the truncation level.

Figures 37 and 38 illustrate the Fussell-Vesely risk importance measures for configuration 295. For the various truncation levels, the results are similar. Figures 39 and 40 show the risk increase ratio results. The results indicate that for 1E-8/yr, 1E-9/yr, and 1E-10/yr truncation levels, the ratio results are similar. However, for the 1E-7/yr truncation level, several basic events have a lower ratio value. These basic events include: AB24KEBF (4.16 kV bus 3B failure), AB348EBF (480 V bus 3B failure), ACB3310R and ACB3320R (breaker transfers open), ACB3208K (breaker transfer closed) and LTKBWSTJ (borated water storage tank failure). These same events show similar results in the Birnbaum plots on Figures 41 and 42. Figure 43 shows the sensitivity of the important components to truncation level.

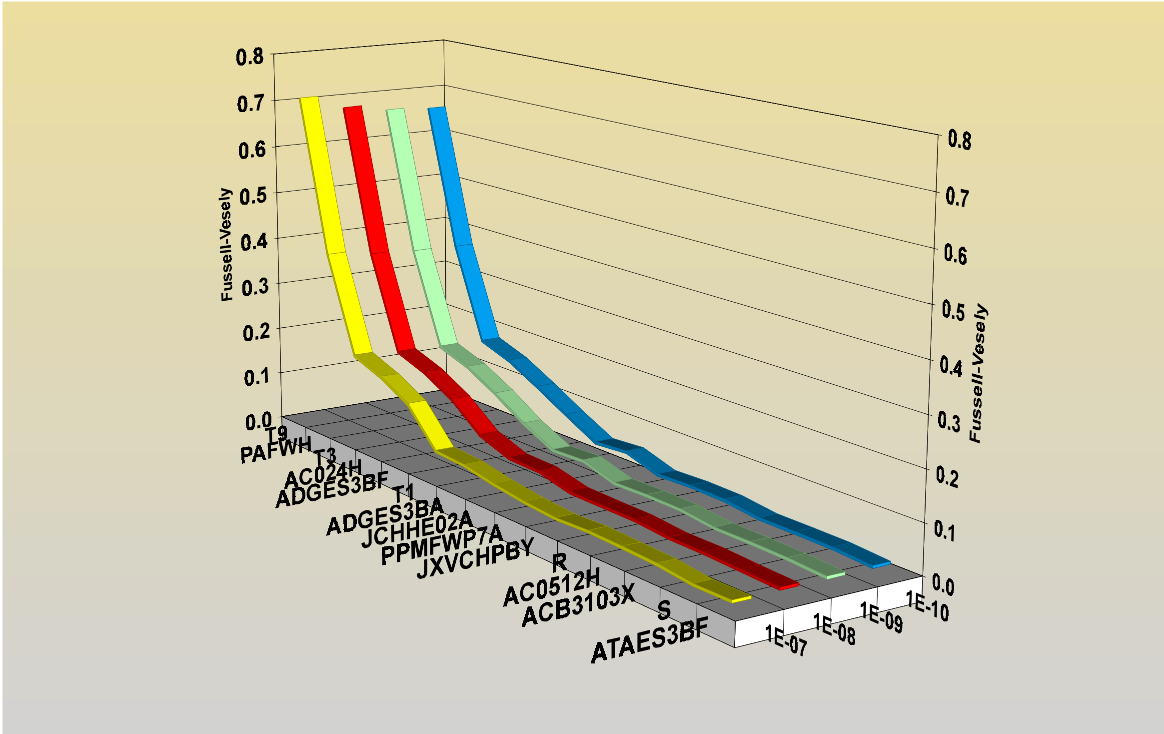

Figure 37. 3-D plot of configuration 295 Fussell-Vesely importance measure results.

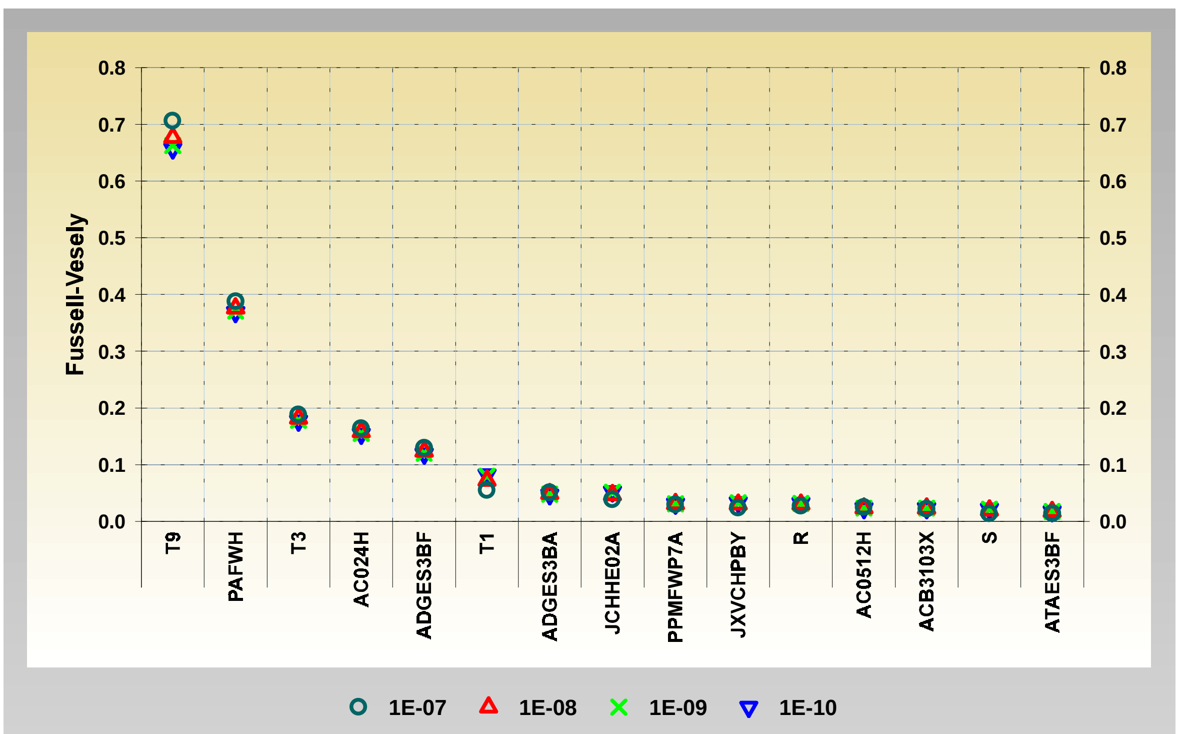

Figure 38. Scatter plot of configuration 295 Fussell-Vesely importance measure results.

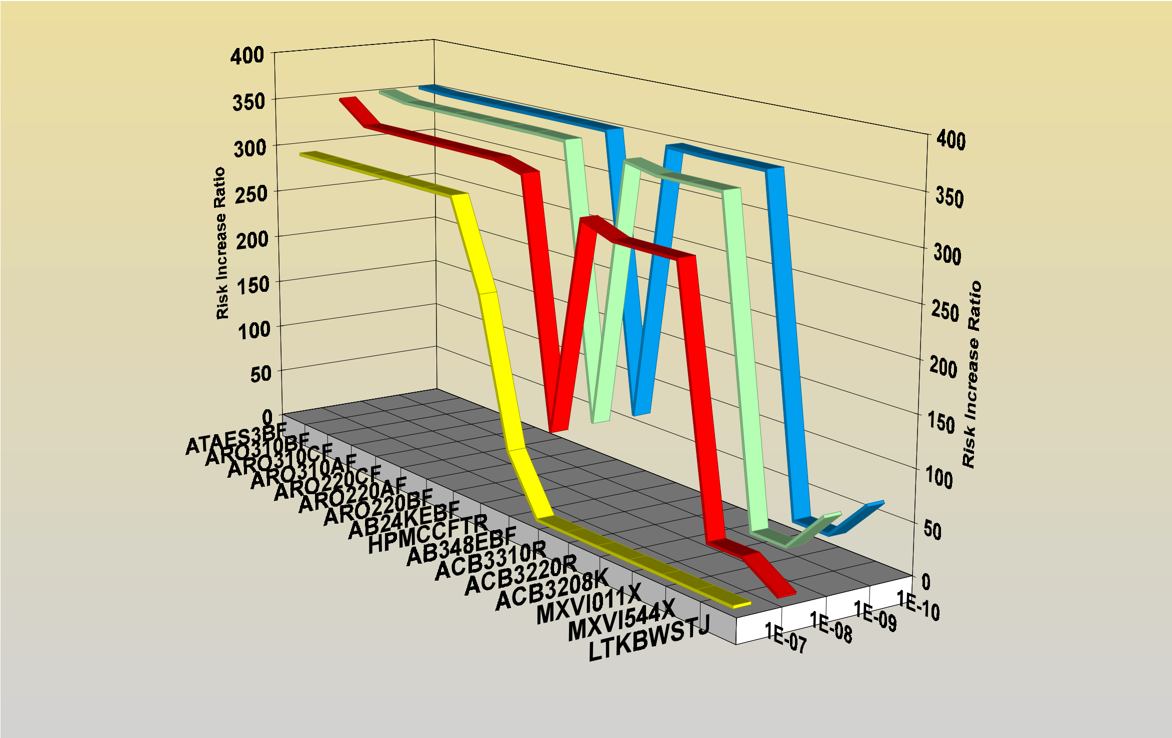

Figure 39. 3-D plot of configuration 295 risk increase ratio results.

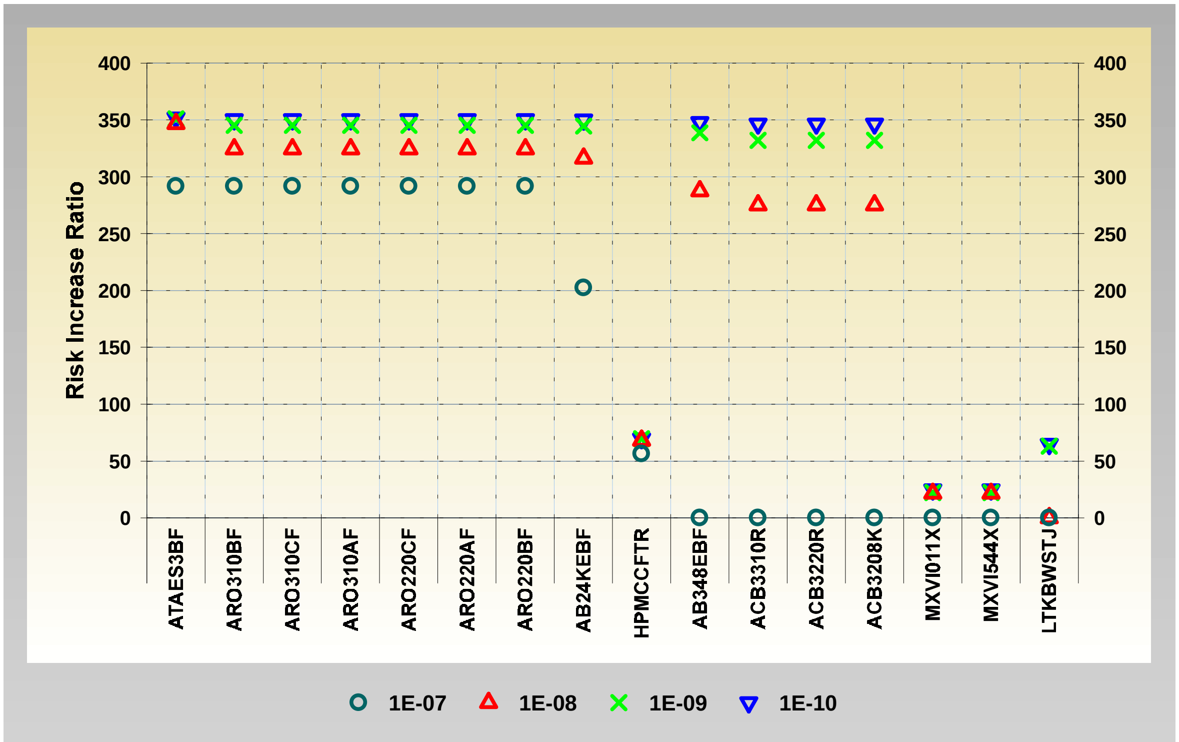

Figure 40. Scatter plot of configuration 295 risk increase ratio results.

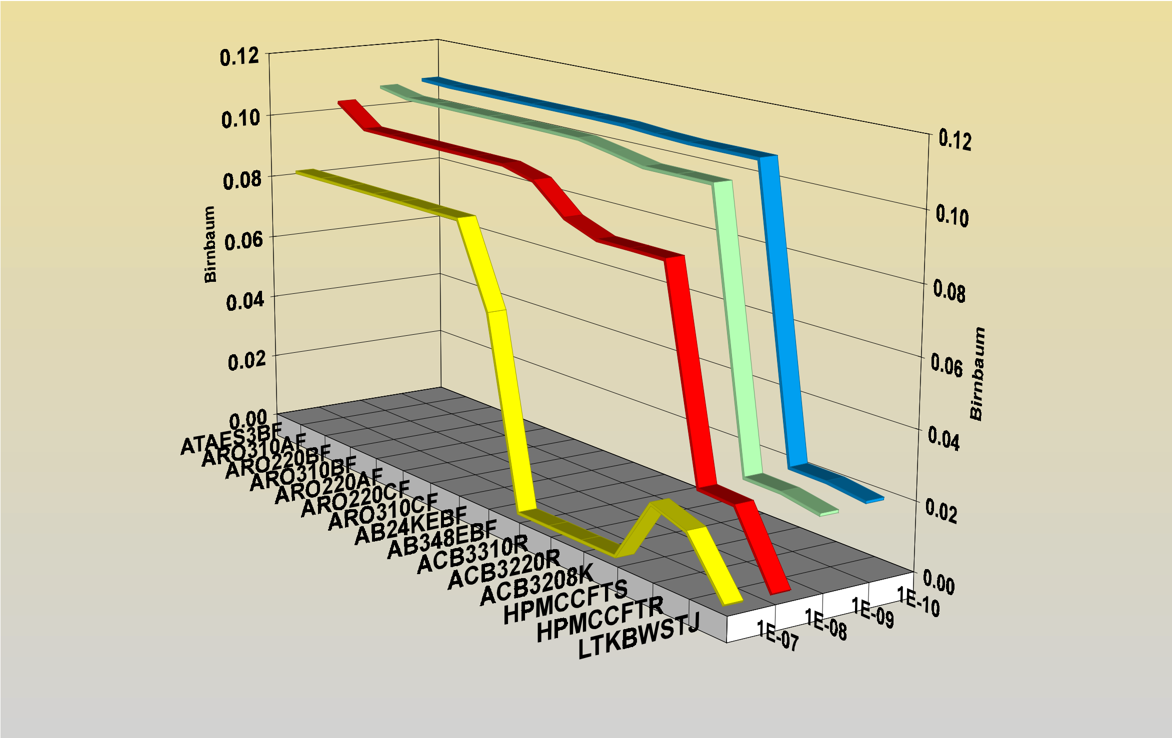

Figure 41. 3-D plot of configuration 295 Birnbaum importance measure results.

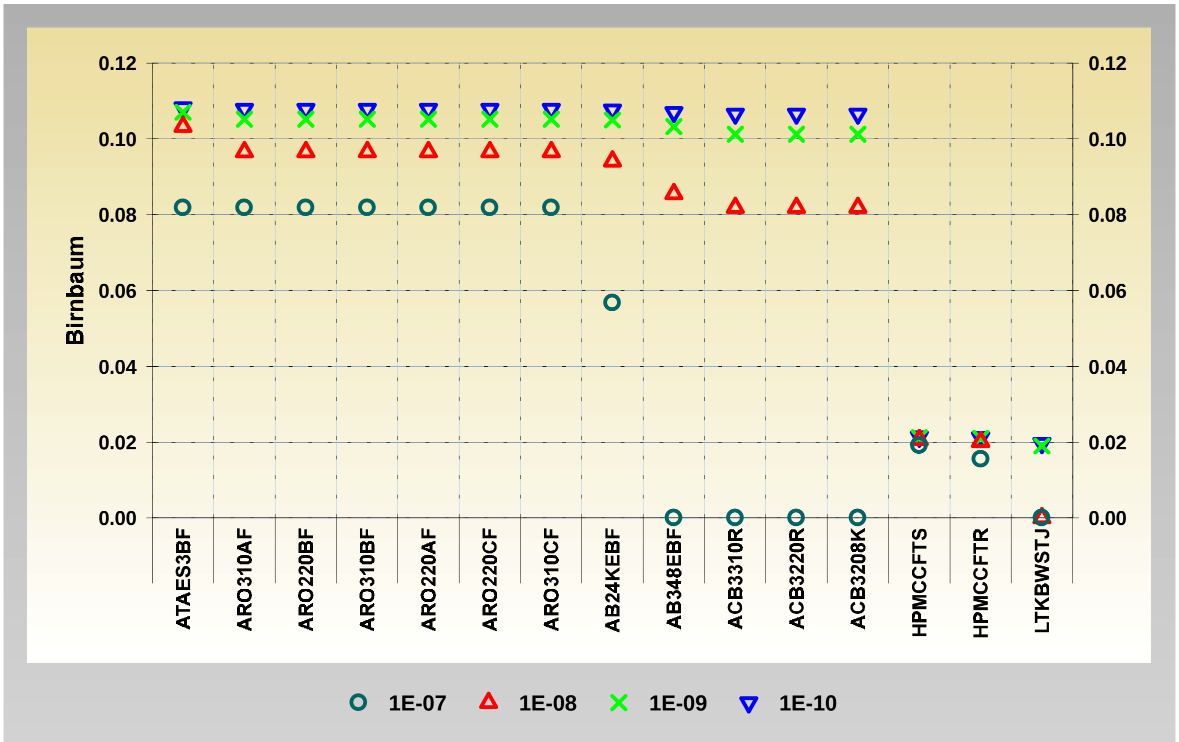

Figure 42. Scatter plot of configuration 295 Birnbaum importance measure results.

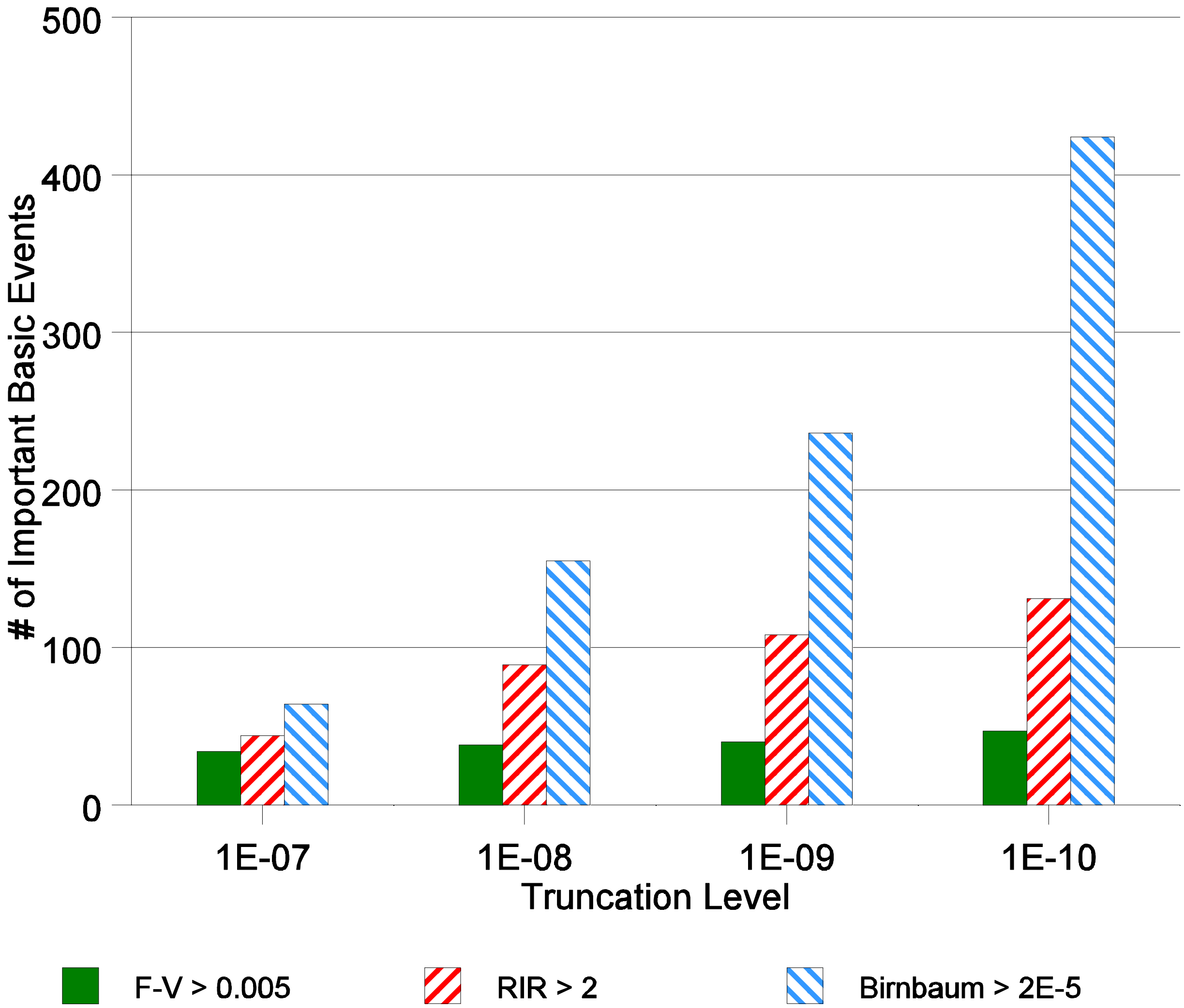

Figure 43. Sensitivity of the number of important basic events to truncation level for configuration 295.

9.0 Treatment of Common-Cause Failure Events

As part of the configuration risk profile analysis, BNL modeled inoperable components by setting the component basic events to TRUE logic events. If the inoperable component had an associated common-cause basic event, these events were set to a FALSE logic event. Setting the common-cause event to FALSE implies that common-cause failure is not possible for the remaining operable components. Modeling inoperable components in this manner may result in nonconservative results.

To more accurately estimate the configuration risk when inoperable components have an associated common-cause event, two sensitivity studies were performed. First, for configuration 221, eight common-cause failure events were modified to account for inoperable components. Second, for configuration 295, one common-cause event was modified to account for inoperable components.

For the first sensitivity case (configuration 221), the following events were adjusted to their respective common-cause beta factors:

SPMDCCFR	= 0.012	SPMR2CFR	= 0.012
SMPDCCFS	= 0.012	SPMR2CFS	= 0.012
LPMCCFTR	= 0.046	SPMR3CFR	= 0.012
LPMCCFTS	= 0.046	SPMR3CFS	= 0.012

The nominal common-cause basic event probability is determined by multiplying the total failure probability (i.e., Q_t) by the respective beta factor (i.e., β). This common-cause parameterization assumes that for a common-cause group, if a component in the group fails, then the conditional probability that the remaining components in the group fails is given by β. Therefore, the common-cause events for the configurations that were evaluated in this section were set to the β value to represent the conditional probability that the remaining components in the common-cause group may fail.

For the second sensitivity case (configuration 295), the following event was adjusted to its common-cause beta factor:

JCHCCFTF = 0.046

The sensitivity analyses were performed using a frequency truncation of 1E-10/yr. For each analysis, the core damage frequency was calculated by regenerating the core damage cut sets (with the new common-cause event probabilities) and then applying the recovery rules. The results of the two sensitivity analyses are shown below in Table 12.

Table 12. Common-cause adjustment sensitivity case results.

Case	Core damage frequency (per year)
Configuration 221 with common-cause events set to logic FALSE.	1.5E-4
Configuration 221 with common-cause events set to conditional probability of group failure (i.e., β).	5.9E-4
Configuration 295 with common-cause events set to logic FALSE.	3.1E-4
Configuration 295 with common-cause events set to conditional probability of group failure (i.e., β).	3.4E-4

As can be seen above, the adjustment of the common-cause parameters for particular configurations can affect the overall core damage frequency results. For configuration 221, the core damage frequency increased by over a factor of three when the common-cause events were set to their respective beta factor probabilities. The analysis for configuration 295 showed a lower increase. The overall sensitivity of the core damage frequency is highly dependent on the type of common-cause modeling and the particular trains or components which are inoperable. No sensitivity analyses were performed to see the impact on core damage frequency as the common-cause beta parameters are varied for the analysis performed in this report. Also, the applicability of the beta values used in the MLD was not questioned by the authors.

Some of the Fussell-Vesely importance measures are plotted in Figure 44 for the configuration 221 sensitivity analysis. The legend of the figure can be interpreted as "BETA-CCF" indicating the importance measures when the common-cause events were set to their conditional probability of group failure (i.e., β). The "NO-CCF" data indicates the importance measures when common-cause events were set to a logic FALSE. As can be seen in the figure, the importance measures do vary, sometimes significantly, as the common-cause events are adjusted.

This details of common-cause parameter adjustment during the analysis for component or train outages is still an open issue for risk-based PRA applications. Further investigations into the area of common-cause modeling and adjustment is required for configuration risk applications. What is evident though, is that the PRA model results are sensitive to common-cause adjustments.

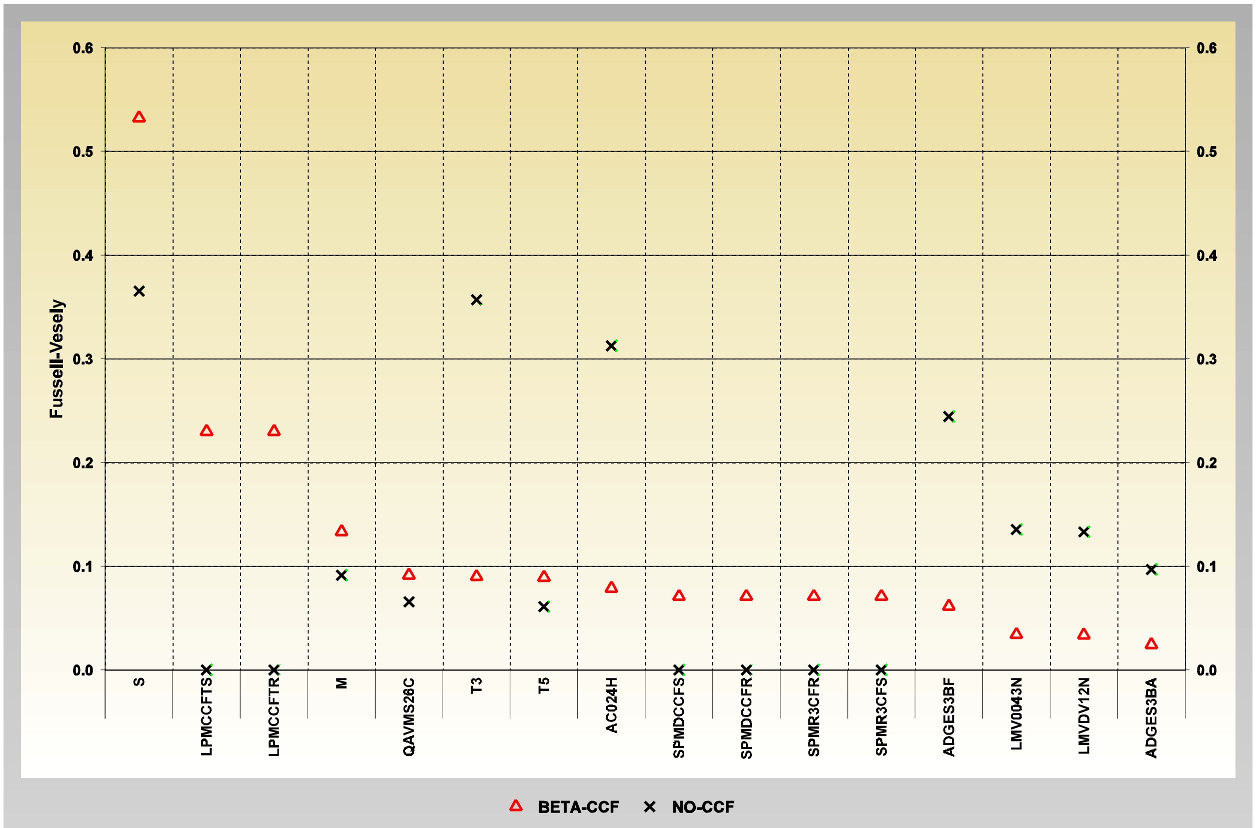

Figure 44. Comparison of Fussell-Vesely importance measures for the cases of common-cause modification (BETA-CCF) and no common-cause modification (NO-CCF).

10.0 Comparison of MLD to Simplified Plant Risk Model

Since a simplified plant risk model (SRM) is available for each plant site,[†] a comparison of this model to the Crystal River MLD could possibly provide further insights into the results (e.g., core damage frequency, importance measures) discussed previously. Thus, the SRM was evaluated and compared to the MLD in order to compare the two models to determine the applicability of the SRM for use in risk-based applications. It was found that modeling and data differences between the two models may limit the ability to draw conclusions based upon model comparisons. Details on the SRM and the comparisons that were performed are discussed below.

The Crystal River Unit 3 SRM is classified as a pressurized water reactor class D reactor plant (primarily Babcock and Wilcox reactors which use low-/high-pressure recirculation for decay heat removal following a LOCA). The classification of this plant stems from the accident sequence precursor program (ASP) grouping of PWRs. The SRM uses an IRRAS linked fault tree/event tree approach to quantifying the accident sequences. Additionally, the data used for the SRM was primarily taken from the Accident Sequence Evaluation Program generic database.[5]

The SRM uses four event trees (plus a transfer to an anticipated transient without scram event tree) and fault trees for each event tree top event. The five event trees used in the model are anticipated transient without scram, loss of offsite power, SGTR, small LOCA, and transient.

The fault trees used in the SRM implement the PWR D event tree split fraction calculations described in the Daily Events Evaluation Manual (DEEM). The DEEM provides split fraction values and references to where and how those values were obtained. The major frontline safety systems, however, have been expanded into simple train level models. This model includes AC power system dependencies. Support systems other than AC power were not modeled.

The basic event values used to quantify the model were obtained from the ASEP database. The other major source for basic event values was the DEEM. The DEEM values were used for those systems that were not expanded into simple train level fault trees. The SRM basic events do not contain uncertainty parameters. Also, test and maintenance unavailabilities are not included in the model (which should not be an issue since test and maintenance events were set to a probability of zero for the configuration analyses). The common cause failure basic events use the Multiple Greek Letter method for estimating common cause failure probabilities.

The SRM was analyzed to obtain an overall core damage frequency. This core damage frequency was compared to the MLD overall core damage frequency. The SRM overall core damage frequency is 7.5E-5/yr while the MLD overall core damage frequency is 1.3E-5/yr. The SRM overall core damage frequency is almost six times greater than the MLD. This difference can be attributed to many different factors. A few of these factors are discussed below.

[†] SRMs have been constructed by the INEL for each plant site as part of the NRC Accident Sequence Precursor, or ASP, program.

One factor in the discrepancy of the core damage frequency is the basic event values that are used to quantify the two models. The SRM primarily uses generic component data and operator action values from the DEEM while the MLD uses plant-specific probabilities for both components and operator actions where possible. The initiating event frequencies are another factor that can be attributed to the difference between the two models. But, the initiating event frequencies used in the SRM are fairly close to those used in the MLD with the exception of the SLOCA initiating event frequency. The SRM SLOCA frequency is a factor of four higher. However, the SLOCA initiating event for the SRM is not dominant as compared to the MLD, so the larger initiating event frequency does not drive the core damage results for the SLOCA sequences.

The last major factor that can cause a difference between the two models is the modeling assumptions. Logic structures for both the SRM and the MLD were reviewed. This review showed different modeling assumptions were used to create the logic. The LOOP accident sequence structure for both models was similar, which resulted in good agreement for these types of accident sequences for the two models.

However, a major difference between the two models can be found when reviewing the modeling assumptions for the SGTR and SLOCA accident sequences. The modeling assumptions for these initiating events are different due to what mitigative systems are allowed to place the reactor in a safe shutdown mode. The modeling assumptions about the decay heat removal system between the two models demonstrates the difference. The SRM models failure of the decay heat removal after the SGTR initiating event as a cause of core damage due to the failure of long-term cooling. The MLD models different recovery actions to the failure of the decay heat removal system after the SGTR initiating event. Therefore, these recovery actions reduce the contribution of the SGTR accident sequences to the overall core damage frequency in the MLD compared to the dominance of the SGTR modeled in the SRM. This explanation (with the recovery modeling now in the SRM rather than the MLD) is why the MLD SLOCA is dominant compare to the SRM SLOCA. The MLD indicates that if high pressure recirculation fails, core damage is the outcome. The SRM models the failure of both decay heat removal and high pressure recirculation as causing core damage. Therefore, the SRM logic modeling lowers the contribution of SLOCA compared to the MLD.

Importance measures for the different initiating events were obtained from the SRM and compared to similar initiating events from the MLD. Importance measures were obtained for the LOOP, SGTR, and SLOCA initiating events. The importance measures for the two models are listed in Tables 13 and 14. Table 13 shows the Fussell-Vesely importance measure for the three initiating events, while Table 14 shows the Risk Increase Ratio importance measure for the three initiating events. The importance measures were also put into bar charts for a visual comparison of the results. The Fussell-Vesely importance measure bar chart for the initiating events is shown in Figure 45. Figure 46 shows the Risk Increase Ratio bar chart for the initiating events.

Table 13. Fussell-Vesely importance measures for the initiating events.

Fussell-Vesely					
LOOP		SGTR		SLOCA	
SRM	MLD	SRM	MLD	SRM	MLD
0.47	0.22	0.44	0.08	0.03	0.35

Table 14. Risk Increase Ratio importance measures for the initiating events.

Risk Increase Ratio					
LOOP		SGTR		SLOCA	
SRM	MLD	SRM	MLD	SRM	MLD
9.6	7.1	31.6	6.0	4.4	177

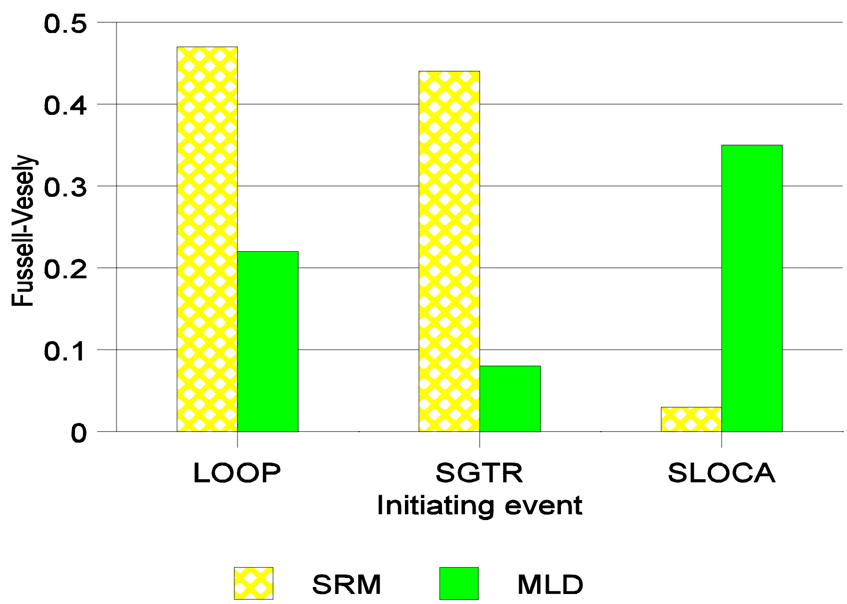

Figure 45. Fussell-Vesely importance measure comparison for select initiating events in the Crystal River MLD and SRM.

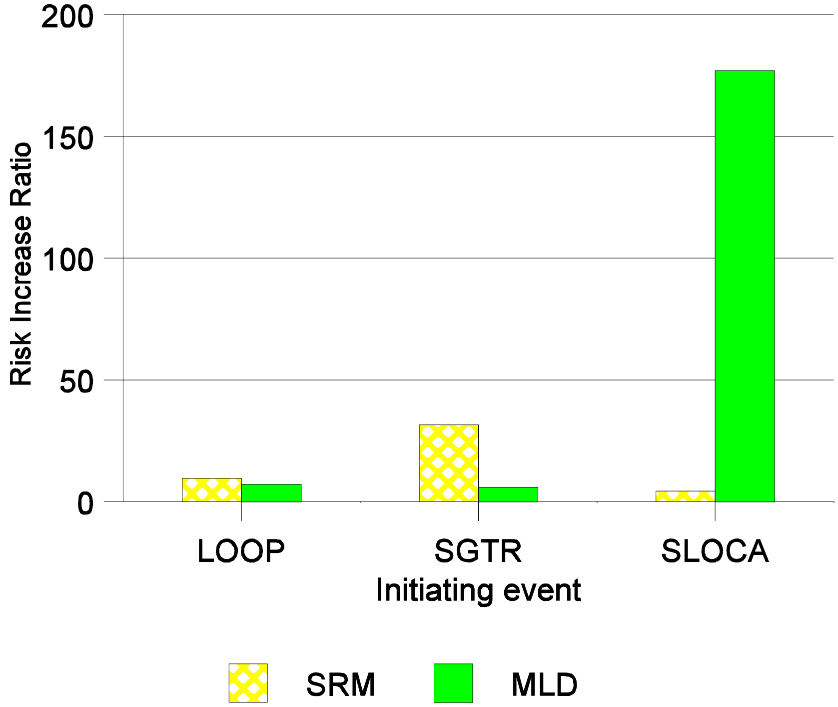

Figure 46. Risk increase ratio importance measure comparison for select initiating events in the Crystal River MLD and SRM.

The Fussell-Vesely importance measure for the LOOP initiating event for both models was different by about a factor of two. The major reason for the difference can be attributed to the initiating event frequency and basic event probabilities for the emergency power system. Another reason for the difference is the total number of initiating events modeled. The SRM models only four initiating events compared to the sixteen initiating events modeled in the MLD, which could potentially shift part of the core damage frequency to other types of initiators.

The Fussell-Vesely importance measure for both the SGTR and SLOCA initiating events for both models was considerably different. The SGTR initiating event for the SRM was higher compared to the MLD. Conversely, the SLOCA Fussell-Vesely for the MLD was higher than the SRM SLOCA Fussell-Vesely. The reason the Fussell-Vesely importance measure is different for these two initiating events can be seen from the dominant accident sequences. The dominant accident sequence for the SRM was a SGTR event, while the dominant accident sequence for the MLD was a SLOCA event. Therefore, these dominant accident sequences resulted in a higher contribution to the Fussell-Vesely importance measures. Once again, the different modeling assumptions between the two models is the primary reason for this difference.

The results for the Risk Increase Ratio importance measure for the two models were the same as those obtained from the Fussell-Vesely importance measure. The LOOP initiating events for both models were approximately the same. The SLOCA Risk Increase Ratio for the SRM was a factor of 40 lower than that for the MLD. The SGTR Risk Increase Ratio for the

MLD was a factor of five lower than that for the SRM. The importance of the dominant accident sequences for the models contributed to the difference of the importance measures obtained for these initiating events.

Configuration 295 was analyzed using both models to compare the core damage frequency results. Configuration 295 contains one inoperable high pressure injection/make-up pump. The make up pump that was failed for the SRM analysis was MUP-1B (this pump was set to failed). The common cause failure of all three make up pumps was adjusted to show that one pump was inoperable (i.e., the common-cause term becomes just βδ).

The core damage frequency for this analysis using the SRM and MLD was 7.2E-4/yr and 3.4E-4/yr, respectively. The two core damage frequencies are different by a factor of almost two. This difference can be attributed to the model complexity, modeling assumptions as discussed above, and failure data used to quantify the models. Another reason for the larger core damage frequency in the SRM is the modeling of the low pressure system. The low pressure injection system is only modeled after the SGTR initiating event in the SRM. The low pressure system, however, is modeled in the MLD as a recovery action to the failure of the high pressure injection system in some initiating events. Also, the low pressure injection system is modeled as an independent system to mitigate core damage in other initiating events. In general, use of the SRM may give only approximate results when compared to the Crystal River MLD. To make further use of the SRM, an analyst would have to identify the modeling assumptions that are driving the core damage frequency results for the particular analysis and compare those assumptions to other documentation such as the plant PRA, IPE, Final Safety Analysis Report, Technical Specifications, etc. Consequently, the SRM was not used further to compare or contrast the MLD for this report.

11.0 Conclusions

The Crystal River Unit 3 plant risk model consists of a MLD and associated basic event data. This MLD is a single fault tree (containing approximately 4,500 gates and 2,500 basic events) representing the dominant accident sequences for core damage. The INEL used this MLD to analyze various plant configurations for a six month span of 1995 operational data. Results of the analysis were provided in the body of this report. Conclusion for specific areas of the report and general conclusion are provided in this section. Specific areas presented in the report were:

- The Crystal River risk model
- The SAPHIRE Representation of the Crystal River Risk Model
- Core Damage Results for Nominal Configuration
- Effects of Recovery Actions on Nominal Core Damage Results
- Sensitivity to Truncation of Nominal Core Damage Results
- Core Damage Results for Important Configurations of Interest
- Effects of Recovery Actions on Important Configurations
- Sensitivity to Truncation of Important Configurations
- Treatment of Common-Cause Failure Events
- Comparison of MLD to Simplified Plant Risk Model

Two concerns for the Crystal River MLD were identified as part of the configuration analysis. First, the MLD may only represent the dominant sequences (from a perspective of nominal conditions) as presented in the IPE. Consequently, using the MLD for configurations where nondominant or unanalyzed sequences become important could cause inaccuracies in the overall core damage results. Second, since the MLD is a fault tree representation of event tree accident sequences, the success paths that would normally be accounted for using event tree analysis could end up being ignored. If the success paths are ignored, the core damage frequency for a particular configuration could be overestimated. The overestimation is believed to be small, but the impact has not been evaluated as part of the work documented in this report.

The original MLD was constructed by the utility using SAIC's CAFTA tools. Converting the MLD for use with the SAPHIRE software turned out to be relatively straightforward. A few minor conversion difficulties were encountered, but these difficulties were overcome, resulting in a useable SAPHIRE risk model. As part of the data conversion, several items were translated from the CAFTA format to the SAPHIRE format. Specifically, the MLD fault tree, associated basic event information, and post-processing recovery rules were all converted by the INEL. Additionally, tasks such as assigning appropriate uncertainty correlation classes for the basic events and loading basic event description data were performed.

For the nominal configuration, the core damage frequency turned out to be 1.1E-4/yr using a frequency truncation of 1E-8/yr. This core damage frequency was obtained before the application of the recovery rules (i.e., before appending recovery actions and removing mutually exclusive events). Also, since the analyses documented in this report are specific to configuration profiling, all testing and maintenance basic events have been set to a probability of zero (FALSE house). The various configurations will have actual testing and maintenance outages "mapped" directly into the model. Consequently, the testing and maintenance "randomness" has been taken out of the PRA model. It was noted that basic event "flags" appear in the cut sets and these flags are used with the recovery rules to append recovery events to appropriate cut sets.

The impact of the application of recovery rules to the core damage cut sets was investigated for the nominal configuration. But, the investigation was complicated by the fact the recovery rules are used for two purposes. The first purpose of the recovery rules is to remove mutually exclusive events (e.g., cut sets with multiple initiating events), while the second purpose is to append recovery actions to core damage cut sets. It is desirable to determine the impact on core damage frequency from only the application of recovery actions onto the cut sets. Consequently, the recovery rules were split into two parts, one for the mutually exclusive events and the second for the actual operator recovery actions. The rules were applied to the core damage cut sets in two steps to see the impact of appending recovery actions after removing mutually exclusive events. For the nominal configuration, the core damage frequency changed from 8.9E-5/yr to 9.5E-6/yr, almost an order of magnitude. This change represents the probability that operators do not restore inoperable components or recover from certain initiating events, and as such, seems reasonable.

Additionally, the nominal configuration was used to explore the sampling convergence of an uncertainty analysis. The results of the uncertainty analysis indicate that the mean nominal core damage frequency is 8E-6/yr and the 95th percentile is 3E-5/yr. The uncertainty sampling appeared to converge after a couple thousand iterations.

After the nominal configuration core damage frequency was generated at a 1E-8/yr truncation, sensitivity analyses were performed to determine the impact on core damage frequency of changing the truncation level. For the nominal configuration, cut sets were generated from levels of 1E-7/yr to 1E-13/yr. While the actual time required to generate the cut sets using IRRAS was not recorded at each truncation level, the analysis time varied from seconds to hours. Results indicate that while the total number of cut sets increases almost exponentially as the truncation level decreases, the core damage frequency approaches an almost constant value (1.3E-5/yr) at a truncation level of 1E-10/yr to 1E-11/yr.

The sensitivity of various importance measures for the nominal configuration was also analyzed to determine impacts of varying the truncation level. For this analysis, three importance measures were calculated: (1) Fussell-Vesely, (2) risk increase ratio, and (3) Birnbaum. For the Fussell-Vesely measure, changes to the truncation level (i.e., from 1E-7/yr to 1E-10/yr) caused only small changes in the Fussell-Vesely value of basic events. For example, the Fussell-Vesely measure changed from 0.44 to 0.36 (from 1E-7/yr to 1E-10/yr, respectively) for the small break LOCA initiating event. The largest absolute Fussell-Vesely change was found for basic event XHPR12H (operator fails to go to high pressure recirculation within 12 hours) which varied from 0.40 to 0.26. But in general, the Fussell-Vesely values for the basic events showed little variation as the truncation level was decreased. Conversely, the risk increase importance measures showed quite dramatic changes as the truncation level was varied. For example, basic event LTKBWSTJ (failure of borated water storage tank) has a risk increase value of zero for truncation levels of 1E-7/yr and 1E-8/yr because this event does not appear in the list of cut sets. However, at a truncation level of 1E-9/yr, this event has a risk increase value of 1,700. Several other events had risk increase values changing from zero to around 200. The Birnbaum importance measure results were similar in that basic events had a zero Birnbaum measure at 1E-7/yr or 1E-8/yr truncation and then appeared at 1E-9/yr (or lower) truncation levels. Once again, the event LTKBWSTJ went from a Birnbaum of zero to a value of 0.019.

For the nominal case, basic event lists were obtained and sorted using the three importance measures at four truncation levels (1E-7/yr to 1E-10/yr). These three basic event lists were used to obtain the total number of "important" components based upon a set of risk criteria. The criteria signifying an "important" component for the three importance measures were: (1) Fussell-Vesely greater than 0.005, (2) risk increase ratio greater than 2.0, or (3) Birnbaum greater than 2E-5/yr. The total number of basic events that appear as "important" with respect to the Fussell-Vesely measure starts out at 35 (at a 1E-7/yr truncation) and increases to about 60 (at a 1E-10/yr truncation). The risk increase ratio and Birnbaum measures show a much larger change in the number of "important" basic events as the truncation level is decreased. Both the risk increase ration and Birnbaum measures indicate 20 to 30 "important" basic events at a 1E-7/yr truncation, but this number increases to over 300 events after the truncation level is lowered to 1E-10/yr. Consequently, an analyst must be aware that truncation levels could have dramatic impacts on the overall number of "important" basic events and the resulting importance measure values.

One could ask then, what truncation level should by used to generate core damage cut sets? The answer to this question depends on the end use of the resulting cut sets, the particular PRA model being used, and the analysis being performed. If one is only estimating core damage frequency with the Crystal River MLD for the nominal case, it is evident that a truncation level of 1E-8/yr to 1E-9/yr is reasonable. But, if one is attempting to classify the "important" basic events based upon the Birnbaum importance measure, it is obvious that even a 1E-10/yr truncation level may not be low enough to capture all of the information required. Consequently, guidance providing a single truncation level to be applied when using a PRA model for risk-based applications is problematic.

In addition to the analyses that were performed for the nominal configuration, four selected plant configurations were investigated. The configuration numbers (basically an identifier) and brief descriptions of the plant configuration are: 36 — makeup valves and service water heat exchanger inoperable, 185 — service water valves inoperable, 221 — reactor building spray pump, service water pumps and check valve, decay heat removal pump, and service water filters all inoperable, and 295 — makeup pump and chiller inoperable. The core damage frequency (before recovery, using a 1E-8/yr truncation) ranged from a high of 2.0E-3/yr (configuration 295) to a low of 1.1E-4/yr (configuration 185) for the four configurations.

For each of the four configurations, the sensitivity to the application of recovery actions was investigated. Like the results for the nominal configuration, application of the recovery actions reduced the core damage frequency by about an order of magnitude. The one exception was for configuration 36, where the core damage frequency was reduced only slightly (from 6.3E-4/yr to 4.7E-4/yr). This slight decrease in core damage frequency could be caused by dominant cut sets (which were originally nondominant) falling outside the scope of the predefined recovery rules. Also, changing the truncation level from 1E-8/yr to 1E-10/yr resulted in only a slight change in core damage frequency, which is consistent with the results seen for the nominal configuration. But, once again, the total number of cut sets that are generated as the truncation level is decreased rises dramatically. For example, when changing the truncation from 1E-8/yr to 1E-10/yr for configuration 295, the total number of cut sets increases from 652 to 11,274, respectively. The actual application of the recovery rules generally reduced the number of cut sets by a factor of two. The resulting core damage frequency (at a 1E-10/yr truncation) for the four configurations were found to be: 36 — 4.7E-4/yr, 185 — 1.3E-5/yr, 221 — 1.5E-4/yr, and 295 — 3.1E-4/yr.

Sensitivity analyses were performed with respect to the truncation level for all four configurations. The issues that were explored as part of these sensitivity analyses include: changed in core damage frequency and number of cut sets, uncertainty results, and impacts on the importance measures. The results of these sensitivity analyses were quite similar to those found from the nominal configuration analyses. Consequently, rather than discusses specific attributes of the results from each configuration, these results will be summarized below. Details concerning the sensitivity analyses for the four analyzed configuration can be found in Section 8.

- All four of the configuration analyses exhibited a convergence of the core damage frequency value at a truncation level around 1E-8/yr. While the core damage frequency increased little as the truncation level was lowered, the total number of cut sets

- The Fussell-Vesely importance measures changed very little as the truncation level was lowered from 1E-7/yr to 1E-10/yr. The analysis for configuration 36 showed almost no change in the Fussell-Vesely importance measures, while the largest change for configuration 185 was from a value of 0.35 to 0.21 for the loss of offsite power initiating event.

- The risk increase importance measures showed wide variations depending on particular truncation levels. The results for configuration 185 were similar to those from the nominal configuration where the borated water storage tank event has a zero risk increase value at a 1E-8/yr truncation but, at the 1E-9/yr truncation, the event appears with a risk increase value of 1,600. Other configuration results contained events that changed from a risk increase value of zero to a value between 10 and 200.

- The Birnbaum importance measure results demonstrated similar outcomes to those seen for the risk increase importance measures. A general pattern was noted that as the truncation level decreased, the Birnbaum measure for a basic event increased. For example, the event AB24KEBF (4.16 kV bus 3B fails) changed from 0.057 to 0.095 and then 0.11 as the truncation was varied from 1E-7/yr to 1E-10/yr.

- The basic events were sorted based upon their importance measures for each configuration to obtain a list of risk “important” basic events. Consequently, three separate lists were obtained, one for the Fussell-Vesely, risk increase ratio, and Birnbaum importance measures. These lists were evaluated to see if the total number of “important” basic events changed as the truncation level was varied, where “important” events are defined as having the measures Fussell-Vesely greater than 0.005, risk increase ratio greater than two, or Birnbaum greater than 2E-5/yr. It was found that when sorted by Fussell-Vesely, the number of risk “important” basic events increased little (less than a factor of two) when the truncation was decreased from 1E-7/yr to 1E-10/yr. Conversely, when evaluating both the risk increase ratio and Birnbaum lists, the total number of risk “important” basic events increased by about a factor of four when the truncation was decreased from 1E-7/yr to 1E-10/yr.

- The parameter uncertainty was evaluated for configurations 185 and 295 for truncation levels from 1E-7/yr to 1E-10/yr. The uncertainty results varied little as the truncation levels were decreased, with the overall spread (i.e., ratio of 95th to 5th percentile) decreasing slightly as the truncation level changed from 1E-7/yr to 1E-10/yr. For configurations 185 and 295, the ratio of the 95th to the 5th percentile was about 30, which is similar to the uncertainty results found for the nominal configuration.

The treatment of parameterization of common-cause basic events for the configuration analyses discussed above was somewhat simplistic. In order to reproduce the results obtained by BNL, the common-cause basic events related to the components that were inoperable during the particular configuration were set to a logic FALSE (i.e., their probabilities were zero). Setting the common-cause failure basic events to a probability of zero during configuration analysis may underestimate the core damage frequency. For example, if one train of a three train system is inoperable, it is possible to experience common-cause failure of the remaining two trains, which would then result in all three trains being inoperable. Setting the common-cause failure event probability to zero for this system implies that the only mechanism that will fail the remaining two trains is random failures of the two trains, which may not be correct.

To evaluate the numerical impact in the core damage frequency when the common-cause basic events are parameterized conditional upon the configuration, two configurations, 221 and 295, were reanalyzed. For these two analyses, the common-cause basic events that were originally set to logic FALSE events were reset to a conditional failure probability value. This conditional probability value is given by β and represents the conditional probability that, given one component failure, the remaining components fail due to common-cause. Consequently, the common-cause basic events for the two configuration that were originally FALSE were reset to a value of β corresponding to their respective component types. The overall impact on the core damage frequency was minimal for configuration 295 (the frequency increased by only a factor of 1.1) while the impact was larger for configuration 221 (the frequency increased by a factor of 3.9). But, issues related to common-cause parameter adjustment during the analysis for component outages still exist and include:

- Providing analyst guidance for common-cause parameter adjustment when using models such as the Beta factor, Multiple Greek Letter, and Alpha factor methods.

- Incorporating the parameter uncertainty for the common-cause basic events during conditional analyses.

- Addressing the common-cause basic event parametization for component outages such as maintenance, testing, independent failures, and (potential) common-cause failures.

Lastly, the a portion of the configuration analyses was repeated using the ASP simplified PRA model in order to determine the applicability of the simplified models to risk-based applications. It was found that modeling and data differences between the MLD and simplified models may limit the ability to draw conclusions based upon model comparisons. To make use of the simplified PRA model, an analyst would have to identify the modeling assumptions that are driving the core damage frequency results for the particular analysis and compare those assumptions to other documentation such as the plant PRA or IPE. Since the simplified PRA models do not currently have support systems modeled in the system fault trees (with the exception of emergency AC power), using the models can prove difficult for configurations dealing with support system outages. But, since the addition of support systems is planned for the next revision of the simplified models, this support systems concern may become less important. Even though the Crystal River 3 simplified model was constructed using modeling assumptions different from those used in the IPE, the simplified models should not be automatically excluded from use in risk-based applications. Instead, the modeling issues that cause differences in core damage frequency between the simplified model and the MLD should be investigated and questioned as part of the analysis. NUREG-1489 discusses NRC Staff use of PRAs and illustrate the complexity when dealing with conflicting modeling assumptions and suggest "...these views [assumptions] should not be combined, but instead should be kept separate for decisionmaking."[6] Model uncertainty is, and will continue to be, an important issue when dealing with the application of PRA models.

12.0 References

1. Florida Power Corporation, *Crystal River 3 Individual Plant Examination*, Docket No. 50-302, March 1993.

2. Modarres, M., *What Every Engineer Should Know About Reliability and Risk Analysis*, Marcel Dekker, Inc., 1993.

3. Russell, K. D. et al., *Systems Analysis Programs for Hands-on Integrated Reliability Evalutations (SAPHIRE) Version 5.0*, NUREG/CR-6116, July 1994.

4. Electric Power Research Institute, *Risk and Reliability Workstation*, 1995.

5. Drouin, M. T, F. T. Harper, and A. L. Camp, *Analysis of Core Damage Frequency from Internal Events; Methodology Guidelines*, NUREG/CR-4550, Vol. 1, September 1987.

6. U.S. Nuclear Regulatory Commission, *A Review of NRC Staff Uses of Probabilistic Risk Assessment*, NUREG-1489, March 1994.